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# A STUDY OF THE CHEMICAL ALTERATION OF BASALT IN THE KILAUEA REGION OF HAWAII[1]

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## ABSTRACT

Chemical analyses of fresh and altered phases of basalt around Kilauea crater in Hawaii National Park indicate that two types of relatively rapid chemical decomposition are taking place. The first type occurs at steam vents where no sulphur dioxide is present. In this case silica and the soluble bases are leached away, leaving the hydrated oxides of aluminum and iron in the form of a characteristic lateritic product. The second type of decomposition is found at the *solfatara*, where sulphur dioxide is present to a variable extent. Here the alteration is accelerated, and the low pH results in the leaching-out of the alkali and alkaline earth elements, aluminum, and iron, leaving a siliceous yellow residue.

These indications have been confirmed by laboratory studies in which fresh rock was subjected to the action of steam, air, and carbon dioxide in various combinations over a period of 6 months.

A white deposit, found abundantly at the *solfatara* of Hawaii National Park, is of interest because it contains 12 per cent more sulphur trioxide than can be combined with the basic elements present. It appears to contain a melanophlogite with a vastly greater amount of "free" $SO_3$ than any reported.

## INTRODUCTION

Rapid alteration of basalt is evident around the *solfatara* and steam vents in the Kilauea region of Hawaii. This alteration appears to be of two distinct types. The first type occurs around the steam cracks, where no sulphur dioxide is present in the vapors. Here sulphur deposits and white incrustations are absent; but brick-red crusts, several inches thick, are found on the rocks that are being attacked. These crusts, being very friable, break down to give a red lateritic residue.

The second type of alteration is found around the *solfatara*, where a more variegated display of color is evidence of greater chemical activity. Sulphur, gypsum, and red ochers are abundant. The older deposits in these areas are masses of yellow, friable material, with only traces of iron, as evidenced by pink colorations. All stages of change from the parent-rock to the final granular yellow deposits are visible.

Petrographically and chemically the mother-rock in both cases is essentially the same. General climatic conditions are the same. The only apparent difference is in the composition of the gases

[1] This work was conducted at the Hawaii National Park and at the University of Hawaii.

emanating from the cracks. A definite relationship, therefore, would be expected to exist between the composition of the gases and the composition of the altered rock. A field and laboratory investigation which gives evidence in support of this thesis is described in this paper.

## HISTORICAL

Whitman Cross[2] describes the lavas of Kilauea as "predominantly olivine-poor basalts." Analyses show the total iron content to be fairly constant, ranging from 10.0 to 14.4 per cent. The aluminum content does not vary greatly with silicon and the individual bases. The most variable constituents in lavas of all types are magnesium oxide and calcium oxide, which range from 0.16 to 21.8 per cent and from 0.86 to 13.9 per cent, respectively. The alkalis are abundant in certain types, and even basaltic types may show more than 5 per cent. The presence of titanium in noteworthy amounts is characteristic of Hawaiian lavas, which average around 3 per cent titanium oxide. Phosphorus is present in only very small amounts.

The composition of the volcanic gases of Kilauea has been studied by A. L. Day and E. S. Shepherd,[3] T. A. Jaggar,[4] E. T. Allen,[5] and S. S. Ballard and J. H. Payne.[6] The gases issuing from the cracks are predominantly steam. Allen reports that the gas from drilled holes at the "Tourist Sulphur Bank" was 96 per cent steam, with carbon dioxide and sulphur dioxide following in order of magnitude. More recently the presence of hydrogen sulphide was detected prior to volcanic activity by J. H. Payne and S. S. Ballard.[7]

Walter Maxwell[8] in 1898 made the first study of soil formation in Hawaii as related to chemical breakdown. He noted the influence of acid vapors in breaking down lava to give various products, including gypsum, alums, red ochers, bauxite, and silicon-rich residues. Samples taken near acid vents were found to contain as much as 70 per cent silica.

Maxwell made a study of the effect of sulphur dioxide and steam on a sample of lava. From 52.9 gm. of lava he found that 1.221 gm. had gone into solution after 4 months. Analysis of the solid showed that silicon had been released by the gases, and the separation of aluminum and the alkalis as sulphates was evident. Iron was the least affected, showing that some of the iron-rich products were residual and not deposited. No explanation was offered for cases where iron was released and silicon was concentrated.

From analytical data from other sections of the Hawaiian Islands, Maxwell came to the conclusion that the lateritic soil, which is predominant in the islands, has been formed as a result of the chemical breakdown of the lava by sulphurous steam.

Hawiian soil-forming processes by weathering were studied by H. S. Palmer[9] in the Wahiawa region of Oahu.

[2] "Lavas of Hawaii and Their Relations," *U.S. Geol. Surv. Prof. Paper 88* (1915).

[3] "Water and Volcanic Activity," *Bull. Geol. Soc. Amer.*, Vol. XXIV (1913), pp. 573–606.

[4] "Magmatic Gases," *Amer. Jour. Sci.*, Vol. CCXXXVIII (1940), pp. 313–53.

[5] "Preliminary Tests of the Gases at Sulphur Banks, Hawaii," *Bull. Hawaiian Volcano Obs.*, Vol. X (1922), pp. 89–93.

[6] *Proc. Hawaiian Acad. Sci., 1937–1938; Bishop Museum Special Pub. 33* (1939), p. 5.

[7] "The Incidence of Hydrogen Sulfide at Kilauea Solfatara Preceding the 1940 Mauna Loa Volcanic Activity," *Science*, Vol. XCII (1940), pp. 218–19.

[8] "Lavas and Soils of the Hawaiian Islands" (Honolulu: Hawaiian Sugar Planters' Assoc., 1898). Pp. 116.

[9] *Soil Sci.*, Vol. XXXI (1931), pp. 253–65.

He found that water and oxygen are added during the conversion of rocks into weathered shells. The increase in oxygen accounted for the apparent increase in iron. Aluminum showed little change, while sulphur and titanium decreased appreciably, but only 10–30 per cent of the phosphorous, silica, ferrous iron, manganese, and alkalis of the original rock remained. The loss of magnesium and calcium was even higher.

## EXPERIMENTAL

*Collection of samples.*—Figure 1 is a map of Kilauea crater showing the location of areas where collections were made in November, 1938. In area *A*, located at the south margin of the main bowl of the Kilauea floor, along the wall rock on the north side of the spit, the gases from the steam vents contain sulphur dioxide. Area *B* is half a mile east of this, and here the steam vents contain no sulphur dioxide. Photographs of the two areas are shown in Figure 2.

Loose and friable deposits were scraped from the rocks or scooped from the beds into specimen bottles. Weathered shells or crusts were chipped from the parent-rock by a hammer, and samples of the unaltered core of the same rock were taken at both locations. For comparative purposes a sample of fresh aa lava from the 1935 flow of Mauna Loa was obtained from Dr. T. A. Jaggar for analysis at the same time.

The following samples were subjected to complete analysis:

1. Parent-rock at sulphur dioxide vents (location *A*)
1*a*. Yellow residual decomposition product from No. 1
2. Parent-rock at steam vents (location *B*)
2*a*. Red residual decomposition product from No. 2
3. Aa lava from 1935 Mauna Loa flow
4. A white deposit from location *A*

*Microscopic description.*—The following microscopic description of the above samples is by Dr. Horace Winchell:

The parent rock of yellow residue, 1, is a normal olivine basalt such as may be found on any of the Hawaiian Islands in the older formations. The texture is intergranular porphyritic. The phenocrysts are feldspar (calcic labradorite with carlsbad and albite twinning and showing normal zoning) and partly iddingsitized olivine. The groundmass is composed of a felty network of plagioclase feldspar laths, of about the same composition as the outermost zones of the labradorite phenocrysts, showing carlsbad and albite twinning but no appreciable zoning. Granular pyroxene, somewhat altered in the specimen studied, fills most of the inter-feldspar space. Its composition is difficult to determine accurately because of the alteration and the fineness of grain-size, but probably lies in the augite-pigeonite portion of the system Diopside-Clinoenstatite-Hedenbergite-$Al_2O_3$. Iron "ores" (magnetite and/or ilmenite) are present as inclusions and as inter-granular crystals between and in the pyroxene grains. A little "ores" is included in marginal feldspar. There is good probability that both magnetite and ilmenite are present, though in the specimen studied, no definite criterion could be established. A very small amount of glassy material occurs with the pyroxene. Apatite probably occurs in tiny euhedral rods inclosed in the feldspar; no sure confirmation of the identity of the mineral could be obtained in the specimen studied, but experience (and presence of $P_2O_5$) shows apatite is a very likely guess.

The yellow residue, 1*a*, appears to consist mostly of opal. This is a hydrous, amorphous form of silica, with variable water content. The index of refraction, 1.435 (to the nearest .005), indicates the water content is of the order of 12% to 16%. The texture of the parent rock is preserved in the opalized material of a solid specimen of the yellow residue, 1*a*. Small amounts of melanophlogite, a *sulfur-trioxide bearing silica*, are present. The identification of this material rests on the index of refraction (1.46) and the fact that in two out of three trials, a definite blackening occurred when samples of the powder were heated before the blowpipe. An unidentified mineral of rather low birefringence and indices of refraction Np = 1.575, Nm about 1.585, and Ng at least 1.59, occurs in very small amount in the yellow

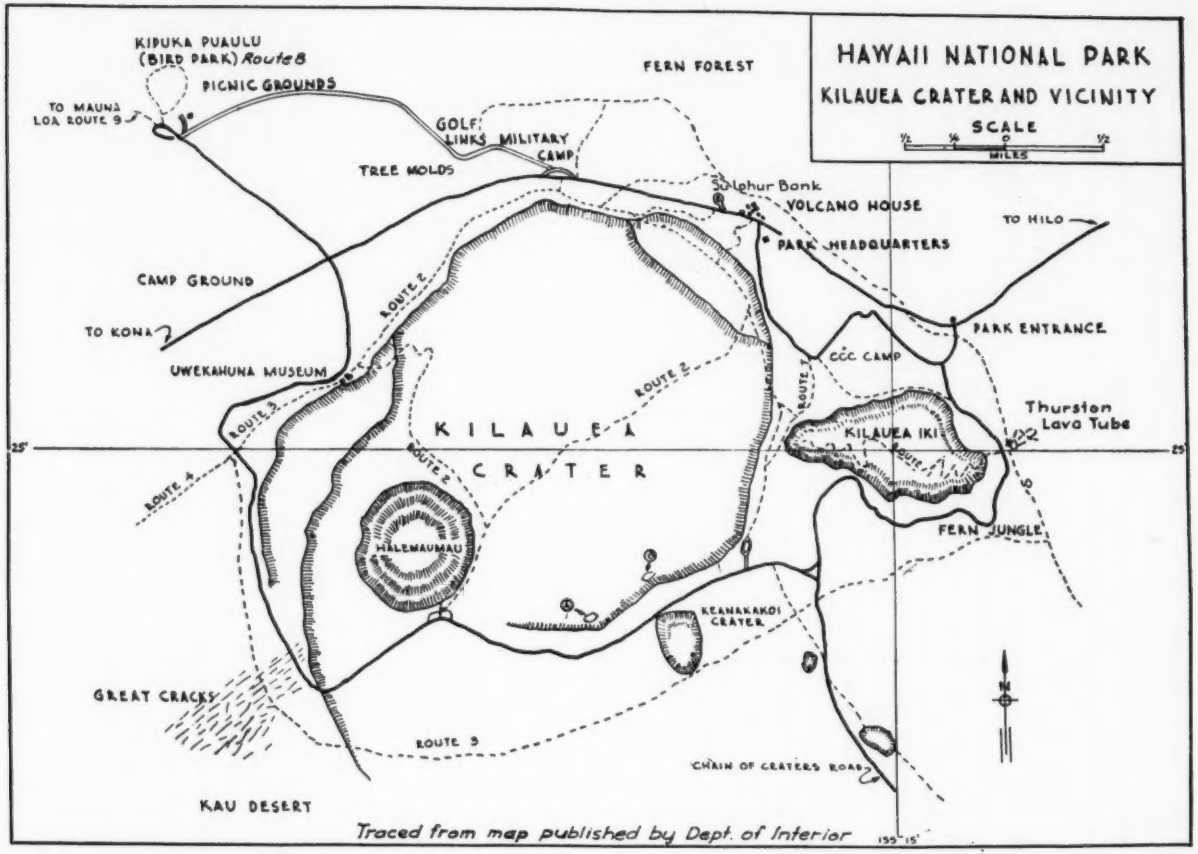


FIG. 1.—Map showing the location where samples were collected. *A*, region of steam and sulphur dioxide. *B*, region of steam activity, sulphur dioxide not detected.

*A*

*B*

FIG. 2.—*Top:* Area *A*, *solfatara; Bottom:* Area *B*, steam vents

powder. No mineral listed in standard optical tables and having a possible chemical composition as indicated by analysis, has these properties, even approximately. This mineral is present in such small amount that it would hardly be worth an attempt to separate and analyze a sample. It is possible that this or some other entirely overlooked mineral of high index and high birefringence and high dispersion may be present and contain the notable titania content shown in the analysis. The indices of refraction and lack of visible dispersion in the unidentified grains mentioned above suggest that these grains do not contain large amounts of titania.

The specimen of parent rock of red residue, 2, contains the following minerals: olivine, pyroxene (composition near diopside 50, hedenbergite 40, clinoenstatite and $Al_2O_3$ 10), "ores," glass, and a fibrous, cryptocrystalline, nearly opaque material which may be altered or devitrified glass. These minerals are typical of a basalt practically identical with that described above under parent rock of yellow residue, 1, except that the larger amount of glass suggests the texture may be intersertal instead of intergranular, at least in part. Without actually studying a specimen of the rock itself, however, no definite statement can be made regarding the texture.

The red residue, 2*a*, is about 95% finely divided, sub-homogeneous, reddish material showing slight evidence of anisotropism perhaps produced by the aggregation of anisotropic, submiscroscopic particles, since no extinction positions can be found in most grains. Very little can be determined optically because of the excessively fine grain of the powder. The red color is probably due to hematite, which is usually subtransparent to subtranslucent, and has an index of refraction appropriate to some of the powder. Clay minerals are undoubtedly present, but no detailed determination is practicable optically because of their finely divided state. An x-ray study would probably make possible the determination of some of the minerals present. A few grains of clear, anisotropic material of index considerably higher than 1.55 may be unaltered residual grains of pyroxene, or they may be some other mineral. No attempt was made to determine their exact nature because of their scarcity.[10]

[10] Private communication, May, 1940.

*Spectrographic analysis.*—The spectrographic analysis of the samples shown in Table 1 was made by Dr. S. S. Ballard at the Experiment Station of the Hawaiian Sugar Planters' Association.

*Methods of analysis.*—The methods of analysis were taken, for the most part, from H. S. Washington,[11] and from W. F. Hillebrand and G. E. F. Lundell.[12] Some modifications were introduced, and these are described in a thesis written by Mau at the University of Hawaii (1940).

TABLE 1

SPECTROGRAPHIC ANALYSIS OF THE SAMPLES

| Amount | 1 | 1*a* | 2 | 2*a* | 3 |
|---|---|---|---|---|---|
| Major >1% | Si<br>Na<br>Ca<br>Fe<br>Al<br>Mg<br>K | Si<br>Ti | Si<br>Al<br>Fe<br>Ti<br>Ca | Si<br>Al<br>Fe<br>Ti | Si<br>Ca |
| Minor 1%–0.01% | Ti<br>Cr<br>V<br>Cu<br>Mn<br>Sr | Al<br>Fe<br>Mg<br>Ca<br>Na<br>K<br>Zr | Mg<br>Mn<br>Zr<br>V<br>Cu<br>Na | Mg<br>Mn<br>Ca<br>Cu<br>Na | Fe |
| Trace <0.01% | Ni<br>Co | Cr<br>Mn | Cr<br>Ni<br>Co<br>Sr<br>Ba | Cr<br>Ni<br>Co | Mg<br>Mn<br>Na |

*Data.*—The analysis of the parent and naturally decomposed rocks are presented in Table 2. These are average figures from duplicate samples.

It is apparent from these analyses that the two parent-rock specimens are essentially the same on the basis of chemical composition. This is of interest in view

[11] *The Chemical Analysis of Rocks* (3d ed.; New York: John Wiley & Sons, Inc., 1919). Pp. 271.

[12] *Applied Inorganic Analysis* (New York: John Wiley & Sons., Inc., 1929). Pp. 929.

of the fact that analyses by O. Silvestri[13] of rocks taken from the caldera walls of Kilauea do not show similar results. However, Cross[14] finds Silvestri's figures in many instances at variance with the normal for Hawaiian rocks. The analyses in Table 2 support the findings of Cross.

When sulphur dioxide is present (Nos. 1 and 1*a*), a vastly different change occurs. There is a marked gain in silicon, a considerable increase in titanium and sulphur, and practically a complete loss of all other constituents except water. Zirconium, which escaped detection in the chemical and spectrographic analysis of the parent-rock, has concentrated to a determinable amount.

TABLE 2

SUMMARY OF THE ANALYSIS OF THE PARENT AND DECOMPOSED ROCKS

(In Percentages)

| Constituent | Parent 1 | Decomposed ($SO_2$) 1*a* | Parent 2 | Decomposed (No $SO_2$) 2*a* |
|---|---|---|---|---|
| $SiO_2$ | 51.83 | 71.74 | 50.79 | 25.82 |
| $Al_2O_3$ | 15.34 | 0.62 | 14.19 | 27.15 |
| $Fe_2O_3$ | 0.98 | 0.10 | 2.14 | 19.45 |
| FeO | 7.85 | o+ | 8.37 | 1.15 |
| MgO | 5.935 | 0.01 | 6.713 | 0.08 |
| CaO | 10.51 | 0.104 | 10.62 | 0.16 |
| $Na_2O$ | 2.06 | o+ | 2.10 | 0.26 |
| $K_2O$ | 0.38 | o+ | 0.869 | 0.12 |
| $+H_2O$ | 1.03 | 1.85 | 0.49 | 11.88 |
| $-H_2O$ | 0.34 | 11.26 | 0.25 | 9.05 |
| $CO_2$ | 0.14 | 0.55 | 0.36 | 0.21 |
| $TiO_2$ | 2.56 | 10.90 | 2.10 | 3.60 |
| $ZrO_2$ | o+ | 0.13 | 0.052 | o+ |
| $P_2O_5$ | 0.21 | o+ | 0.23 | 0.28 |
| $SO_2$ | 0.18 | 2.71 | 0.03 | 0.16 |
| Cl | 0.018 | 0.021 | 0.042 | o+ |
| S | 0.22 | o+ | 0.10 | 0.14 |
| $Cr_2O_3$ | 0.057 | 0.037 | 0.073 | 0.201 |
| $V_2O_5$ | 0.054 | o+ | 0.059 | o+ |
| NiO | 0.044 | o+ | 0.016 | 0.023 |
| CuO | 0.087 | o+ | 0.066 | 0.069 |
| MnO | 0.144 | o+ | 0.329 | 0.138 |
| SrO | 0.02 | o+ | 0.03 | o+ |
| BaO | o+ | o+ | 0.01 | o+ |
| Total | 99.989 | 99.968 | 100.029 | 99.941 |
| Less O for Cl and S | − 0.117 | − 0.009 | − 0.069 | − 0.070 |
| Total | 99.87 | 99.96 | 99.96 | 99.87 |

TABLE 3

AVERAGES OF THE ANALYSES OF THE PARENT AND DECOMPOSED ROCKS RECALCULATED TO A TOTAL OF 100

(In Percentages)

| Constituent | Parent 1 | Decomposed ($SO_2$) 1*a* | Parent 2 | Decomposed (No $SO_2$) 2*a* |
|---|---|---|---|---|
| $SiO_2$ | 51.90 | 71.77 | 50.81 | 25.859 |
| $Al_2O_3$ | 15.36 | 0.62 | 14.20 | 27.19 |
| $Fe_2O_3$ | 0.98 | 0.10 | 2.14 | 19.48 |
| FeO | 7.86 | o+ | 8.37 | 1.15 |
| MgO | 5.943 | 0.01 | 6.713 | 0.08 |
| CaO | 10.53 | 0.04 | 10.63 | 0.16 |
| $Na_2O$ | 2.06 | o+ | 2.10 | 0.26 |
| $K_2O$ | 0.38 | o+ | 0.869 | 0.12 |
| $+H_2O$ | 1.03 | 1.85 | 0.49 | 11.90 |
| $-H_2O$ | 0.34 | 11.271 | 0.25 | 9.05 |
| $CO_2$ | 0.14 | 0.55 | 0.36 | 0.21 |
| $TiO_2$ | 2.56 | 10.90 | 2.10 | 3.60 |
| $ZrO_2$ | o+ | 0.13 | 0.052 | o+ |
| $P_2O_5$ | 0.21 | o+ | 0.23 | 0.28 |
| $SO_2$ | 0.18 | 2.71 | 0.03 | 0.16 |
| Cl | 0.018 | 0.021 | 0.042 | o+ |
| S | 0.22 | o+ | 0.10 | 0.14 |
| $Cr_2O_3$ | 0.057 | 0.037 | 0.073 | 0.201 |
| $V_2O_5$ | 0.054 | o+ | 0.059 | o+ |
| NiO | 0.044 | o+ | 0.016 | 0.023 |
| CuO | 0.087 | o+ | 0.066 | 0.069 |
| MnO | 0.144 | o+ | 0.329 | 0.138 |
| SrO | 0.02 | o+ | 0.03 | o+ |
| BaO | o+ | o+ | 0.01 | o+ |
| Total | 100.117 | 100.009 | 100.069 | 100.070 |
| Less O for Cl and S | − 0.117 | − 0.009 | − 0.069 | − 0.070 |
| Total | 100.00 | 100.00 | 100.00 | 100.00 |

The changes occurring during the decomposition of the rocks are very significant. Where steam alone is present (Nos. 2 and 2*a*), it will be noted that the changes consist, aside from hydration, in a loss of silicon, a gain of aluminum, and an oxidation of ferrous to ferric iron. There is almost complete loss of magnesium, alkaline earths, and alkalis. Titanium, sulphur, and chromium show an apparent gain.

In order to eliminate the effects of oxidation and hydration, the data in Table 2 have been recalculated to total 100, and one constituent has been assumed to remain constant. $TiO_2$ is held constant for the decomposition in the presence of sulphur dioxide (Nos. 1 and 1*a*) and $Al_2O_3$ in the presence of steam alone (Nos. 2 and 2*a*). Table 3 gives the analyses of Table 2, recalculated to 100;

[13] *Com. geol., Ital. boll.*, Vol. XIX (1888), pp. 128–47, 168–96.

[14] See ftn. 2.

Table 4 shows the relative changes in the presence of sulphur dioxide, holding $TiO_2$ constant; and Table 5 the relative changes in the presence of steam alone, holding $Al_2O_3$ constant.

the constituents except silica and titania have been leached away. In the absence of sulphur dioxide, the iron and aluminum remain, along with the silica and titania. Thus conditions of such high

TABLE 4

RELATIVE CHANGES RESULTING FROM DECOMPOSITION BY STEAM IN PRESENCE OF SULPHUR DIOXIDE, ASSUMING $TiO_2$ CONSTANT

(In Percentages)

| Constituent | Change in Original Rock | | | Change in Each Constituent | | |
|---|---|---|---|---|---|---|
| | I Remaining | II Loss | III Gain | IV Remaining | V Loss | VI Gain |
| $SiO_2$ | 16.9 | 35.0 | ..... | 32.5 | 67.5 | ..... |
| $Al_2O_3$ | 0.15 | 15.2 | ..... | 0.08 | 99.0 | ..... |
| $Fe_2O_3$ | 0.02 | 0.96 | ..... | 2.04 | 98.0 | ..... |
| FeO | 0 | 7.86 | ..... | 0 | 100 | ..... |
| MgO | 0+ | 5.95 | ..... | 0 | 100 | ..... |
| CaO | 0.01 | 10.5 | ..... | 0.09 | 99.9 | ..... |
| $Na_2O$ | 0 | 2.06 | ..... | 0 | 100 | ..... |
| $K_2O$ | 0 | 0.38 | ..... | 0 | 100 | ..... |
| $+H_2O$ | 0.43 | 0.60 | ..... | 41.8 | 58.2 | ..... |
| $-H_2O$ | 2.65 | ..... | 2.31 | 779 | ..... | 679 |
| $CO_2$ | 0.13 | 0.01 | ..... | 92.9 | 7.14 | ..... |
| $TiO_2$ | 2.56 | 0 | ..... | 100 | 0 | ..... |
| $ZrO_2$ | 0.13 | ..... | 0.13 | 0 | ..... | ∞ |
| $P_2O_5$ | 0 | 0.21 | ..... | 0 | 100 | ..... |
| $SO_3$ | 0.65 | ..... | 0.46 | 356 | ..... | 256 |
| Cl | 0+ | 0.02 | ..... | 0 | 100 | ..... |
| S | 0 | 0.22 | ..... | 0 | 100 | ..... |
| $Cr_2O_3$ | 0.01 | 0.05 | ..... | 16.7 | 83.3 | ..... |
| $V_2O_5$ | 0 | 0.05 | ..... | 0 | 100 | ..... |
| NiO | 0 | 0.04 | ..... | 0 | 100 | ..... |
| CuO | 0 | 0.09 | ..... | 0 | 100 | ..... |
| MnO | 0 | 0.14 | ..... | 0 | 100 | ..... |
| SrO | 0 | 0.02 | ..... | 0 | 100 | ..... |
| BaO | 0 | 0.02 | ..... | 0 | 100 | ..... |
| Total | 23.5 | 79.4 | 2.80 | ..... | ..... | ..... |

In Tables 4 and 5 the last three columns give the percentage remaining, lost, or gained by each constituent referred to its total amount as 100. Figures 3 and 4 show graphically the changes taking place for the major constituents.

The differences in the two types of decomposition are striking. In the presence of sulphur dioxide, practically all

acidity as obtain around the *solfatara* give rise to the siliceous residual deposits. Decomposition by steam and weathering alone give the red lateritic residues, which are high in iron and alumina.

Moisture is abundant at Kilauea, and this plays an important role in speeding up the decomposition processes in that area. In drier regions the same processes

occur at a much slower rate, so that soil formation may be a matter of years rather than weeks, as it is at Kilauea.

### LABORATORY DECOMPOSITION

In order to test these findings in the laboratory, studies were made of the effect of various gases on fresh rock. The parent-rock for these studies was a sample of aa lava collected from the 1935 flow of Mauna Loa by Dr. T. A. Jaggar. This sample was used because it had been subjected to no weathering action, having been collected hot while the lava was still flowing at a rate of 100 feet per hour.

The rock sample was prepared by crushing in a steel mortar and sifting. Material passing through a No. 16 sieve but retained by a No. 30 sieve was used, 50-gm. samples of the rock were suspended in platinum gauze cylinders in a 2-liter flask, as illustrated in Figure 5. The flask, fitted with a reflux condenser, was maintained at the boiling-point of water by immersion in an oil bath. Gases were introduced through side tubes at the rate of approximately 0.1 cc. per second.

Five separate samples were treated with the following combinations of gases for an uninterrupted period of six months.

TABLE 5

RELATIVE CHANGES RESULTING FROM DECOMPOSITION BY STEAM IN ABSENCE OF SULPHUR DIOXIDE, ASSUMING $Al_2O_3$ CONSTANT

(In Percentages)

| CONSTITUENT | CHANGE IN ORIGINAL ROCK | | | CHANGE IN EACH CONSTITUENT | | |
|---|---|---|---|---|---|---|
| | I Remaining | II Loss | III Gain | IV Remaining | V Loss | VI Gain |
| $SiO_2$ | 13.5 | 37.31 | ..... | 26.6 | 73.4 | ..... |
| $Al_2O_3$ | 14.2 | 0 | ..... | 100 | 0 | ..... |
| $Fe_2O_3$ | 10.2 | ..... | 8.03 | 475 | ..... | 375 |
| FeO | 0.60 | 7.77 | ..... | 7.17 | 92.8 | ..... |
| MgO | 0.04 | 6.67 | ..... | 0.60 | 99.4 | ..... |
| CaO | 0.08 | 10.5 | ..... | 0.75 | 99.2 | ..... |
| $Na_2O$ | 0.14 | 1.96 | ..... | 6.67 | 93.3 | ..... |
| $K_2O$ | 0.06 | 0.81 | ..... | 6.90 | 93.1 | ..... |
| $+H_2O$ | 6.21 | ..... | 5.72 | 1,270 | ..... | 1170 |
| $-H_2O$ | 4.72 | ..... | 4.47 | 1,890 | ..... | 1790 |
| $CO_2$ | 0.11 | 0.25 | ..... | 30.6 | 69.4 | ..... |
| $TiO_2$ | 1.88 | 0.22 | ..... | 89.5 | 10.5 | ..... |
| $ZrO_2$ | 0 | 0.05 | ..... | 0 | 100 | ..... |
| $P_2O_5$ | 0.15 | 0.08 | ..... | 65.2 | 34.8 | ..... |
| $SO_3$ | 0.08 | ..... | 0.05 | 267 | ..... | 167 |
| Cl | 0 | 0.04 | ..... | 0 | 100 | ..... |
| S | 0.07 | 0.03 | ..... | 70.0 | 30.0 | ..... |
| $Cr_2O_3$ | 0.10 | ..... | 0.03 | 143.0 | ..... | 42.8 |
| $V_2O_5$ | 0 | 0.06 | ..... | 0 | 100 | ..... |
| NiO | 0.01 | 0.01 | ..... | 50.0 | 50.0 | ..... |
| CuO | 0.04 | 0.03 | ..... | 57.1 | 42.9 | ..... |
| MnO | 0.07 | 0.26 | ..... | 21.2 | 78.8 | ..... |
| SrO | 0 | 0.03 | ..... | 0 | 100 | ..... |
| BaO | 0 | 0.01 | ..... | 0 | 100 | ..... |
| Total | 52.2 | 66.1 | 18.3 | ..... | ..... | ..... |

Sample

I. Steam and air
II. Steam and carbon dioxide
III. Steam, air, and carbon dioxide
IV. Steam, air, and sulphur dioxide
V. Steam, air, carbon dioxide, and sulphur dioxide.

The samples were then removed for examination. Samples I, II, and III showed no visible change. Samples IV and V, however, were covered with a white deposit within 3 months and at the end of 6 months had a heavy deposit on the lower portion, as shown in Figure 6.

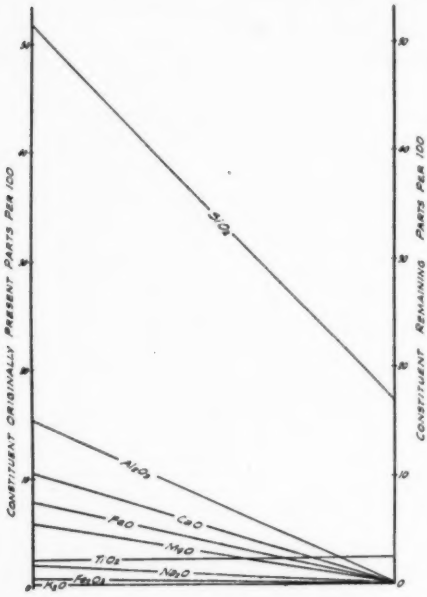


FIG. 3.—Comparison of changes produced by steam in the presence of sulphur dioxide. $TiO_2$ is held constant and the changes in other constituents compared with it.

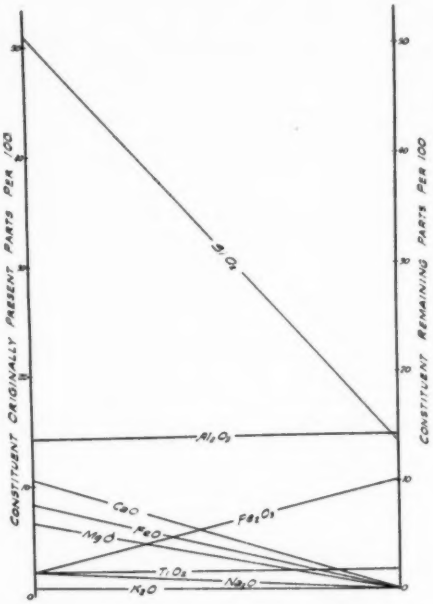


FIG. 4.—Comparison of changes produced by steam in the absence of sulphur dioxide. $Al_2O_3$ is kept constant and the changes in other constituents compared with it.

The analysis of the original rock and of the five samples subjected to the action of the various gases are presented in Table 6. It will be noted that the analysis of the original rock is very similar to that of the parent-rocks in Table 2. The 1935 sample has a higher ferric oxide content and a lower percentage of total water, however. Exposure to the air in a small piece at the high temperature of the lava flow probably accounts for the higher ferric oxide content, while the low water content would be expected for the same reason and also because there had been no hydration due to weathering. The possibility of ascertaining the relative age of lava flows in a given area by measuring the extent of the hydration is indicated.

Samples I, II, and III, where no sulphur dioxide was present, show little change from the parent-rock. There is some increase in the ferric oxide content with a corresponding decrease in the

ferrous oxide content, however, as well as a slight increase in total water and a small loss of alkalis and alkaline earths.

In Samples IV and V the presence of the sulphur dioxide has greatly altered the composition. In order to obtain a better picture of the changes which have taken place, the analyses of the parent-rock and Samples IV and V have been recalculated to 100 per cent, as shown in Table 7; then in Tables 8 and 9 the titania content has been held constant, and the percentage change has been calculated as previously with the naturally decomposed material.

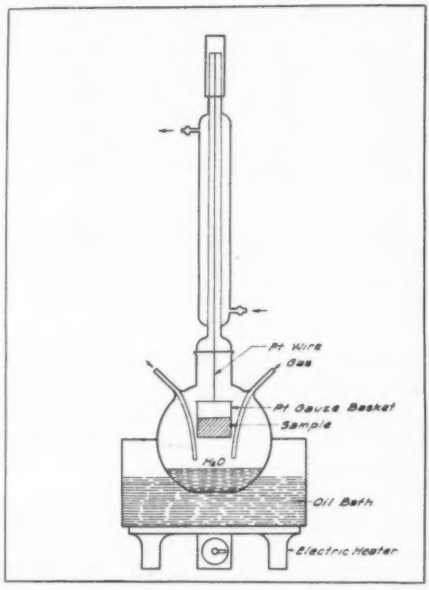


FIG. 5

These changes are shown graphically in Figures 7 and 8. It is seen that there has been a gain both in water and in sulphur trioxide. All the other constituents show substantial losses. Magnesia shows the highest loss, reaching 76 per cent in Sample V. Silica remains with the smallest loss, with a maximum of 28 per cent in Sample IV. The changes are the same that occurred in the rock undergoing natural decomposition at the *solfatara*. If the process were allowed to continue, a final residue similar to that found naturally would undoubtedly remain. The evidence from the laboratory work confirms, therefore, the field observation with regard to the breakdown mechanism. Some evidence as to the speed of this breakdown is given likewise.

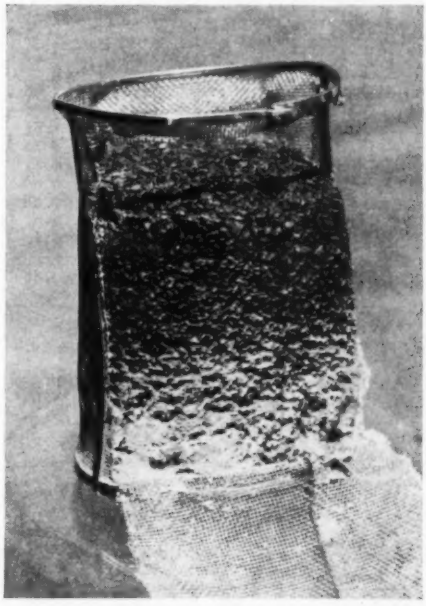

FIG. 6.—Decomposition of lava sample after 6 months of exposure under the combined action of steam, air, and sulphur dioxide. Note the lower zone, which is white with soluble salts leached out from above.

### THE WHITE DEPOSIT

The residues in area *A*, where sulphur dioxide is present, are characterized by the presence of white incrustations and deposits. In some instances one can reach beneath lava ledges or into cracks and

TABLE 6

ANALYSES OF 1935 ROCK AND SAMPLES SUBJECTED TO VARIOUS GASES FOR 6 MONTHS

(In Percentages)

| Constituent | 1935 Parent-Rock | I Subjected to $H_2O$, Air | II Subjected to $H_2O$, $CO_2$ | III Subjected to $H_2O$, Air, $CO_2$ | IV Subjected to $H_2O$, Air, $SO_2$ | V Subjected to $H_2O$, Air, $SO_2$, $CO_2$ |
|---|---|---|---|---|---|---|
| $SiO_2$ | 52.73 | 52.75 | 52.53 | 52.89 | 44.66 | 51.83 |
| $Al_2O_3$ | 15.57 | 15.79 | 16.01 | 15.97 | 7.97 | 7.71 |
| $Fe_2O_3$ | 3.95 | 4.39 | 4.86 | 4.52 | 3.10 | 3.24 |
| FeO | 6.33 | 6.27 | 5.39 | 5.61 | 2.36 | 1.84 |
| MgO | 7.28 | 7.14 | 7.04 | 6.99 | 2.98 | 2.03 |
| CaO | 9.21 | 9.08 | 9.20 | 9.18 | 6.74 | 8.65 |
| $Na_2O$ | 1.90 | 1.82 | 1.69 | 1.80 | 1.31 | 1.40 |
| $K_2O$ | 0.25 | 0.20 | 0.22 | 0.19 | 0.16 | 0.17 |
| $+H_2O$ | 0.10 | 0.13 | 0.13 | 0.14 | 5.00 | 4.01 |
| $-H_2O$ | 0.04 | 0.08 | 0.05 | 0.06 | 8.21 | 4.05 |
| $CO_2$ | 0.10 | 0.0+ | 0.08 | 0.03 | 0.0+ | 0.02 |
| $TiO_2$ | 2.13 | 2.07 | 2.15 | 2.22 | 2.51 | 2.48 |
| $SO_3$ | 0.10 | 0.10 | 0.08 | 0.04 | 15.08 | 12.51 |
| Total | 99.69 | 99.82 | 99.43 | 99.64 | 100.08 | 99.94 |

TABLE 7

ANALYSES OF THE 1935 ROCK AND SAMPLES IV AND V FROM TABLE 7, RECALCULATED TO TOTAL OF 100

(In Percentages)

| Constituent | 1935 Parent-Rock | IV Subjected to $H_2O$, Air, $SO_2$ | V Subjected to $H_2O$, Air, $SO_2$, $CO_2$ |
|---|---|---|---|
| $SiO_2$ | 52.89 | 44.64 | 51.86 |
| $Al_2O_3$ | 15.61 | 7.96 | 7.72 |
| $Fe_2O_3$ | 3.96 | 3.10 | 3.24 |
| FeO | 6.35 | 2.36 | 1.84 |
| MgO | 7.31 | 2.98 | 2.03 |
| CaO | 9.24 | 6.72 | 8.66 |
| $Na_2O$ | 1.91 | 1.31 | 1.40 |
| $K_2O$ | 0.25 | 0.16 | 0.17 |
| $+H_2O$ | 0.10 | 5.00 | 4.01 |
| $-H_2O$ | 0.04 | 8.20 | 4.05 |
| $CO_2$ | 0.10 | 0 | 0.02 |
| $TiO_2$ | 2.14 | 2.51 | 2.48 |
| $SO_3$ | 0.10 | 15.06 | 12.52 |
| Total | 100.00 | 100.00 | 100.00 |

obtain handfuls of the pure white mass. The same material was found in the laboratory decomposition in the presence of sulphur dioxide. This residue has been variously described as gypsum and silica. Examination and analysis shows it to be a unique mineral.

Dr. Horace Winchell describes the deposit as follows:

> The white deposit is composed mainly of gypsum and melanophlogite, with a very small amount of opal, probably less than 5%. The gypsum composes more than half of the sample. It is easily identified microscopically by its cleavages, optic orientation, and indices of refraction (Nm about 1.522). Melanophlogite is identified by its isotropic nature, its index of refraction 1.460 (published accounts of this mineral give 1.461 to 1.45?), and by the fact that it turns dark when heated before the blowpipe. The chemical analysis of the white powder indicates that the melanophlogite must contain considerably more sulfur trioxide than that described, however, and this possibility should be studied further, with chemical and x-ray studies and perhaps further optical work.

The chemical analysis given in Table 10 shows that the essential constituents are sulphur trioxide, silicon dioxide, calcium oxide, and water. It is obvious

TABLE 8

RELATIVE CHANGES IN SAMPLE IV RESULTING FROM LABORATORY DECOMPOSITION BY STEAM, AIR, AND SULPHUR DIOXIDE, ASSUMING $TiO_2$ CONSTANT

(In Percentages)

| CONSTITUENT | CHANGE IN ORIGINAL ROCK | | | CHANGE IN EACH CONSTITUENT | | |
|---|---|---|---|---|---|---|
| | I Remaining | II Loss | III Gain | IV Remaining | V Loss | VI Gain |
| $SiO_2$ | 38.1 | 14.8 | ..... | 71.9 | 28.1 | ..... |
| $Al_2O_3$ | 6.79 | 8.82 | ..... | 43.5 | 56.5 | ..... |
| $Fe_2O_3$ | 2.64 | 1.32 | ..... | 66.7 | 33.3 | ..... |
| FeO | 2.01 | 4.34 | ..... | 31.8 | 68.2 | ..... |
| MgO | 2.54 | 4.77 | ..... | 34.8 | 65.2 | ..... |
| CaO | 5.74 | 3.50 | ..... | 62.1 | 37.9 | ..... |
| $Na_2O$ | 1.12 | 0.79 | ..... | 58.6 | 41.4 | ..... |
| $K_2O$ | 0.14 | 0.11 | ..... | 56.0 | 44.0 | ..... |
| $+H_2O$ | 4.26 | ..... | 4.16 | 4,260 | ..... | 4,160 |
| $-H_2O$ | 6.99 | ..... | 6.95 | 17,500 | ..... | 17,400 |
| $CO_2$ | 0 | 0.10 | ..... | 0 | 100.0 | ..... |
| $TiO_2$ | 2.14 | 0 | ..... | 100 | 0 | ..... |
| $SO_3$ | 12.8 | ..... | 12.7 | 12,800 | ..... | 12,700 |
| Total | 85.3 | 38.6 | 23.8 | ..... | ..... | ..... |

TABLE 9

RELATIVE CHANGES IN SAMPLE V RESULTING FROM LABORATORY DECOMPOSITION BY STEAM, AIR, SULPHUR DIOXIDE, AND CARBON DIOXIDE, ASSUMING $TiO_2$ CONSTANT

(In Percentages)

| CONSTITUENT | CHANGE IN ORIGINAL ROCK | | | CHANGE IN EACH CONSTITUENT | | |
|---|---|---|---|---|---|---|
| | I Remaining | II Loss | III Gain | IV Remaining | V Loss | VI Gain |
| $SiO_2$ | 44.8 | 8.14 | ..... | 84.6 | 15.4 | ..... |
| $Al_2O_3$ | 6.66 | 8.95 | ..... | 42.7 | 57.3 | ..... |
| $Fe_2O_3$ | 2.80 | 1.16 | ..... | 70.7 | 29.3 | ..... |
| FeO | 1.59 | 4.76 | ..... | 25.0 | 75.0 | ..... |
| MgO | 1.75 | 5.56 | ..... | 23.9 | 76.1 | ..... |
| CaO | 7.47 | 1.77 | ..... | 80.8 | 19.2 | ..... |
| $Na_2O$ | 1.21 | 0.70 | ..... | 63.4 | 36.6 | ..... |
| $K_2O$ | 0.15 | 0.10 | ..... | 60.0 | 40.0 | ..... |
| $+H_2O$ | 3.46 | ..... | 3.36 | 3460 | ..... | 3360 |
| $-H_2O$ | 3.49 | ..... | 3.45 | 8730 | ..... | 8630 |
| $CO_2$ | 0.02 | 0.08 | ..... | 20.0 | 80.0 | ..... |
| $TiO_2$ | 2.14 | ..... | ..... | 100 | 0 | ..... |
| $SO_3$ | 10.8 | ..... | 10.7 | 10800 | ..... | 10700 |
| Total | 86.3 | 31.2 | 17.5 | ..... | ..... | ..... |

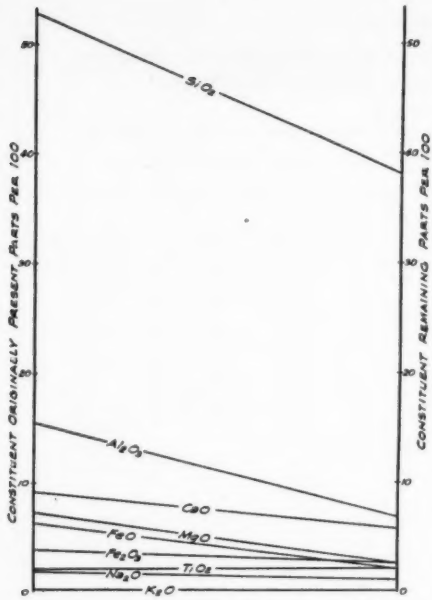


FIG. 7.—Comparison of changes produced by steam, air, and sulphur dioxide (Sample IV). $TiO_2$ is kept constant and the changes in other constituents compared with it.

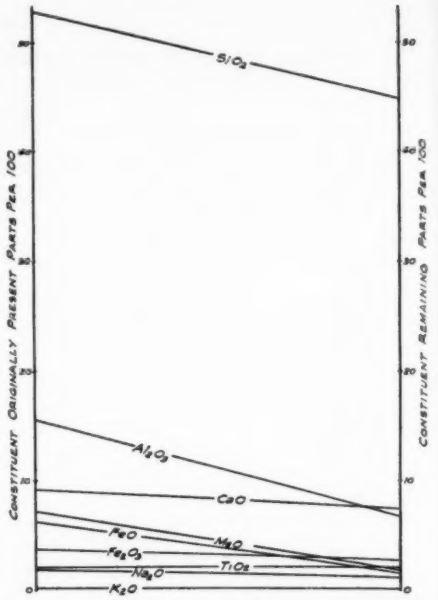


FIG. 8.—Comparison of changes produced by steam, air, carbon dioxide, and sulphur dioxide (Sample V). $TiO_2$ is kept constant and the changes in other constituents compared with it.

TABLE 10

ANALYSIS OF WHITE DEPOSIT

(In Percentages)

| Constituent | Sample I | Sample II | Average |
|---|---|---|---|
| $SiO_2$ | 32.85 | 32.67 | 32.76 |
| $Al_2O_3$ | o+ | o+ | o+ |
| $Fe_2O_3$ | 0.193 | 0.207 | 0.200 |
| FeO | o+ | o+ | o+ |
| MgO | o+ | o+ | o+ |
| CaO | 17.01 | 17.13 | 17.07 |
| $Na_2O$ | o+ | o+ | o+ |
| $K_2O$ | o+ | o+ | o+ |
| $-H_2O$ | 13.66 | 13.55 | 13.60 |
| $TiO_2$ | o+ | o+ | o+ |
| $ZrO_2$ | o+ | o+ | o+ |
| $P_2O_5$ | 0.016 | 0.018 | 0.017 |
| $SO_3$ | 36.58 | 36.46 | 36.52 |
| S | o+ | o+ | o+ |
| $Cr_2O_3$ | o+ | o+ | o+ |
| MnO | o+ | o+ | o+ |
| SrO | o+ | o+ | o+ |
| BaO | o+ | o+ | o+ |
| Total | ..... | ..... | 100.17 |

at once that there is a considerable excess of acidic constituents over basic constituents. The microscopic examination proves the presence of gypsum. Assuming all the calcium is in the form of gypsum, there remains an excess of 12.15 per cent sulphur trioxide and 2.63 per cent water. There is no other basic element which can combine with the excess sulphur trioxide. It is apparent, therefore, that the silicon dioxide has taken up sulphur trioxide, as well as water of hydration. A similar mineral, but containing a much lower percentage of sulphur trioxide, known as "melanophlogite," is found in Sicily.

ACKNOWLEDGMENT.—The authors wish to acknowledge the valuable assistance of Dr. T. A. Jaggar, Mr. E. C. Wingate, Dr. Horace Winchell, Dr. S. S. Ballard, and Dr. J. E. Hoffmeister in various phases of this investigation.

# THE METEORITIC IMPACT ORIGIN OF THE MOON'S SURFACE FEATURES

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## ABSTRACT

The craters on the moon appear to have been formed by meteoritic impact rather than by volcanism. This mode of origin is suggested by their size, shape, distribution, associated features, and other considerations. Many of the aspects of lunar craters, such as their circular shape and the presence of central peaks, which have been considered as disproof of their impact origin, are the result of the crater's being formed by explosion rather than by percussion. Variation of the physiographic form of these craters, with increase in their size from small, cup-shaped pits to large, walled plains, is mainly due to modification and melting by superheated molten lava, generated by the impact in the case of the larger craters. Maria are probably extensive lava plains generated by the impact of bodies of asteroidal dimensions and were formed relatively late in lunar history, as is indicated by the physiographic youth of the superimposed post-maria craters. Aside from the shape of the craters and the maria, the small mass of the moon and its low internal pressure make volcanism unlikely in the lunar environment.

## INTRODUCTION

When Galileo pointed the first telescope toward the moon in 1609, he became the first human to observe its mountains and craters. Since then, selenographers have observed, studied, and mapped the moon's surface in such painstaking detail that it has been said that the portion of the moon facing toward our planet is better known in many respects than any equivalent portion of the earth. Nevertheless, there is no general agreement concerning the origin of the features on the moon's surface. Most interpretations can be classified in two general categories: (1) that the features are the result of volcanism or some related type of internal magmatic activity and (2) that the features are the result of the impact of meteorites and related extra-lunar bodies with the moon's surface. Nearly all astronomy texts discuss both theories but favor volcanism, inasmuch as it appears to have a large majority of proponents. The present writer has, however, been impressed with the fact that all the major topographical forms on the moon, including the craters, the maria, and most of the mountains, can be explained most satisfactorily by the impact of extra-lunar bodies. In addition, volcanism and diastrophism do not seem to have played an important part in fashioning the features on the moon. Some evidence supporting this thesis is presented in this paper.

## THE LUNAR ENVIRONMENT

The moon revolves around the sun at a velocity of 19 miles per second and around the earth at a velocity of about ½ mile per second in a slightly elliptical orbit and at an average distance of 239,000 miles. Therefore, a direct head-on lunar collision with a meteorite traveling at the solar parabolic velocity of 26½ miles per second would impinge at 45 miles per second, whereas the less common tail-end collision would strike at a velocity of about 8 miles per second. Relative to the earth, the moon completes one revolution and one rotation simultaneously in a period of 27⅓ days,

so that the moon always presents the same face toward the earth. Owing to actual and apparent librations of the moon, earth-dwellers see a total of 59 per cent of the moon's surface, the remaining 41 per cent being invisible.

The lunar diameter of 2,160 miles is about one-fourth that of the earth, so that the volume of the moon is one forty-ninth that of our planet. However, because the lunar specific gravity is only 3.3 while the specific gravity of the earth is 5.5, the total mass of the moon is only one eighty-first that of the earth. The total lunar surface area is $14\frac{1}{2}$ million square miles, or about $7\frac{1}{2}$ per cent that of the earth. The 59 per cent of the moon that the earth-dwellers can observe is, therefore, $8\frac{1}{2}$ million square miles, or approximately equivalent to the area of North America.

Because of the relatively small lunar mass, the force of gravity on the moon's surface is only one-sixth that of the force of gravity on the earth's surface. Thus, even heavy basic rocks, if such are present on the moon's surface, can be displaced and thrown about more readily that equal-sized blocks of pumice on the earth. Owing to the low lunar gravity, lunar features will have many times—possibly six times—the linear dimensions of features on the earth produced by equal forces.

Observations show that the moon does not have, and theoretical consideration suggests that the moon never has had, an atmosphere. The absence of an atmosphere eliminates nearly all the familiar terrestrial gradational forces, such as wind or water action. Nor can there be extensive oxidation or hydration or formation of sedimentary rocks. However, a popularly held impression that the moon is a completely changeless world is probably not justified, for examination of lunar features clearly shows them to be in various stages of erosion. In view of the absence of most of the usual erosional agents, erosion of the moon must be extremely slow and must be accomplished, for the most part, (1) by catastrophic action, including blast action, melting by lava and hot gases, moonquakes, and flying missiles, and (2) by insolation. The great variation in temperature on the moon's surface from above the boiling-point of water to about $-250°$ F. must have a slow, but nevertheless considerable, pulverizing effect on the outer few yards of the lunar lithosphere. In addition to the mechanical disintegration, the expansion and contraction of rock produces a mass downgrade creep,[1] which slowly reduces the angle of slope of lunar surfaces. Given sufficient time, molecular flow or solifluction and "micro-isostatic" adjustments may also cause gradation.

## CRATERS

### GENERAL

The most conspicuous lunar features are the craters, of which over thirty thousand have been identified. Although these features are of a second order of magnitude as compared to the maria and the terrae,[2] the correct interpretation

[1] C. F. S. Sharpe, *Landslides and Related Phenomena* (New York: Columbia University Press, 1938), p. 28.

[2] For the purposes of this paper, the word "terra" (plural, "terrae") is used to refer to all the light-colored areas of the moon's surface, as contrasted with the dark areas or "maria" (singular, "mare"). The writer is unaware of any previous use of this term other than by Kepler, who wrote: "Do maculos esse maria, do lucidas esse terras." This statement is quoted by C. Fisher in *The Story of the Moon* (Garden City, N.Y.: Doubleday, Doran & Co., 1945), p. 104, as possibly originating the misnomer "maria" (Latin, "seas"), whereas the word "terra" has apparently never been commonly used. It is convenient to divide the terrae into four areas: (1)

of the craters holds the key to the origin of other lunar features. It is therefore desirable, first, to describe and analyze some of the aspects of lunar craters which, the writer believes, show that these features can be explained only as a result of the impact of extra-lunar bodies.

SIZE

The discernible lunar craters vary in size from small, lipped, cup-shaped pits less than a mile in diameter, which the telescope is barely able to resolve, to huge, walled plains, such as Calvius (142 miles in diameter, 20,000 feet deep). Between these two extremes there are medium-sized craters (Figs. 1–4), characterized by one or more central peaks, such as Theophilus (Fig. 1), 64 miles in diameter, 16,000 feet deep; Tycho (Fig. 2), 56 miles in diameter, 12,000 feet deep; and Copernicus (Fig. 4), 56 miles in diameter, 12,000 feet deep. Although the craters tend to develop different characteristics with variation in size, there are gradations between all types, suggesting that all have a similar origin. The small pits and the large, walled plains cannot be considered end-members of the crater family, since there are probably numerous small pits beyond the resolving power of the telescope and since, as the writer attempts to show below, the maria are probably to be considered large craters.

The large size of lunar craters has been cited as evidence that the forces which created the lunar landscape were of a much greater magnitude than any which the earth has experienced. However, because of the small force of the moon's gravity, one should divide the linear dimensions of lunar craters possibly by a factor of 6 when comparing them with terrestrial craters. Thus, some of the largest terrestrial calderas may be comparable to the large lunar craters. But, according to H. Williams,[3] all large calderas are primarily due to crustal collapse caused by the withdrawal of magmatic support. He states that volcanic explosion craters on the earth, unmodified by slumping, do not exceed 1 mile in diameter. Therefore, although the lunar craters are probably not larger than those that can be produced by volcanic forces, the proponent of lunar volcanism must postulate extensive subsidence or volcanic explosions of proportions unknown in geological experience to account for the large size of many lunar craters.

Although the size of a volcanic explosive crater is apparently limited, the size of an impact crater is dependent only upon the size of the impinging missile. One can predict, then, that impact craters will be of assorted sizes and will exhibit little tendency toward a "standard" or limiting size. Although the effect of the impact of such a high-velocity missile is imperfectly understood, there is sufficient evidence to show that a high-order explosion results.[4] Therefore, since the resulting crater is formed by explosion rather than by percussion, a relatively small meteorite can produce an enormous crater in the lunar environment. Boon and Albritton[5] have calculated that a body only 250 feet in diameter and with an impact velocity of about 19 miles per second contains suffi-

Terra Australis, Southland, (2) Terra Orientalis, Eastland, (3) Terra Borealis, Northland, and (4) Terra Occidentalis, Westland.

[3] "The Caldera Problem," *Proc. Geol. Soc. Amer., 1937* (1938), p. 257.

[4] J. D. Boon and C. C. Albritton, Jr., "The Impact of Large Meteorites," *Field and Laboratory*, Vol. VI (1938), pp. 56–64; C. C. Wylie, "Meteoric Craters, Meteors, and Bullets," *Pop. Astr.*, Vol. XLII (1934), pp. 469–71.

[5] See ftn. 4.

FIG. 1.—The moon, age 19 days. Photograph is oriented with south at the top, in accordance with astronomical convention. Photograph by Mount Wilson Observatory.

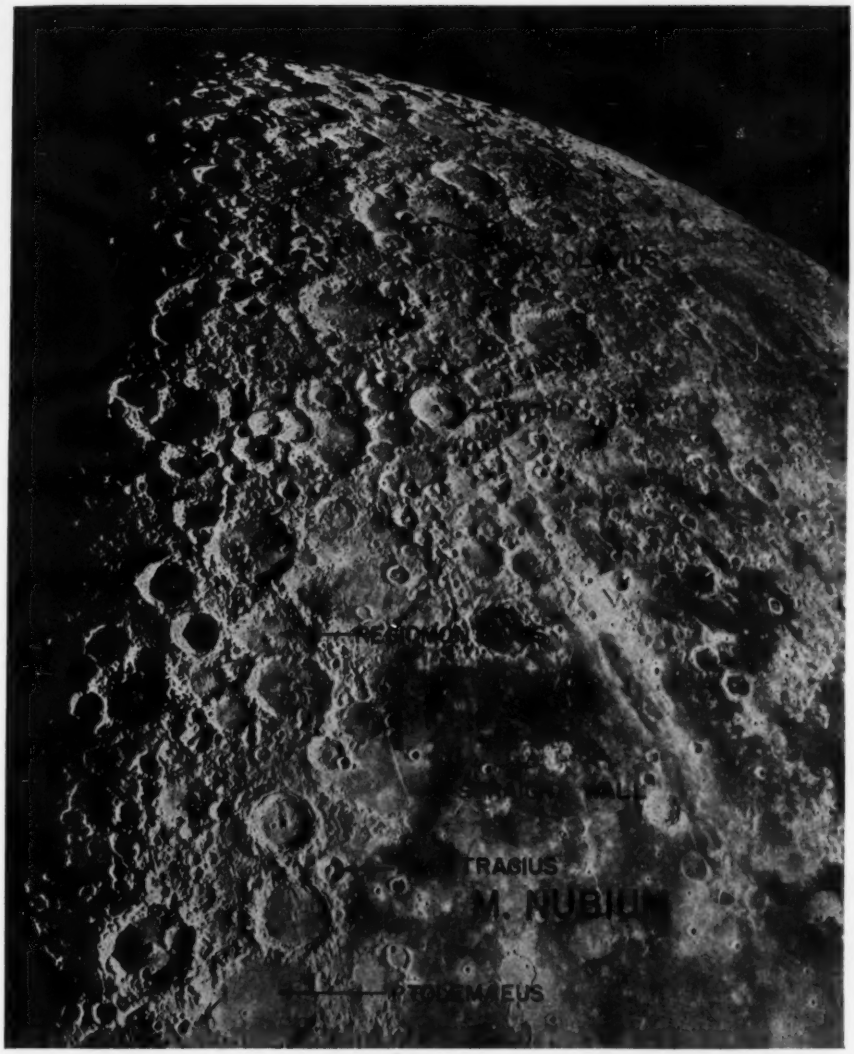


FIG. 2.—Southern portion of the moon, showing part of Mare Nubium and part of Terra Australis. Mare Nubium appears to be a thin lava plain only partially inundating an old terra surface. Youthful craters are superimposed on the mare, whereas youthful, mature, and old-age craters cover the terra. Note the linear arrangements of the craterlets marked *r*. Photograph by Mount Wilson Observatory.

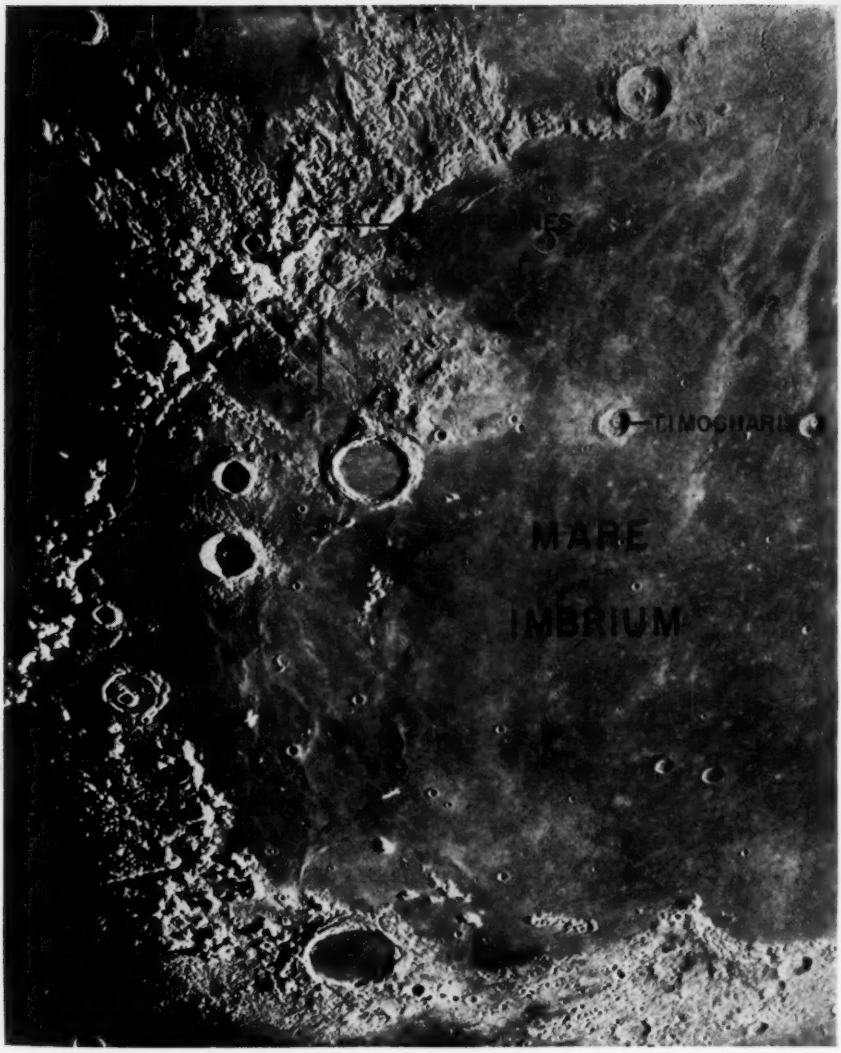


FIG. 3.—Mare Imbrium and vicinity. The lunar mountains surrounding Mare Imbrium appear to be masses of explosion-scoured rubble, with a few superimposed youthful craters formed after the Imbrium impact. Note the rill or crevice marked *1* and the winding maria ridges marked *2*. Photograph by Mount Wilson Observatory.

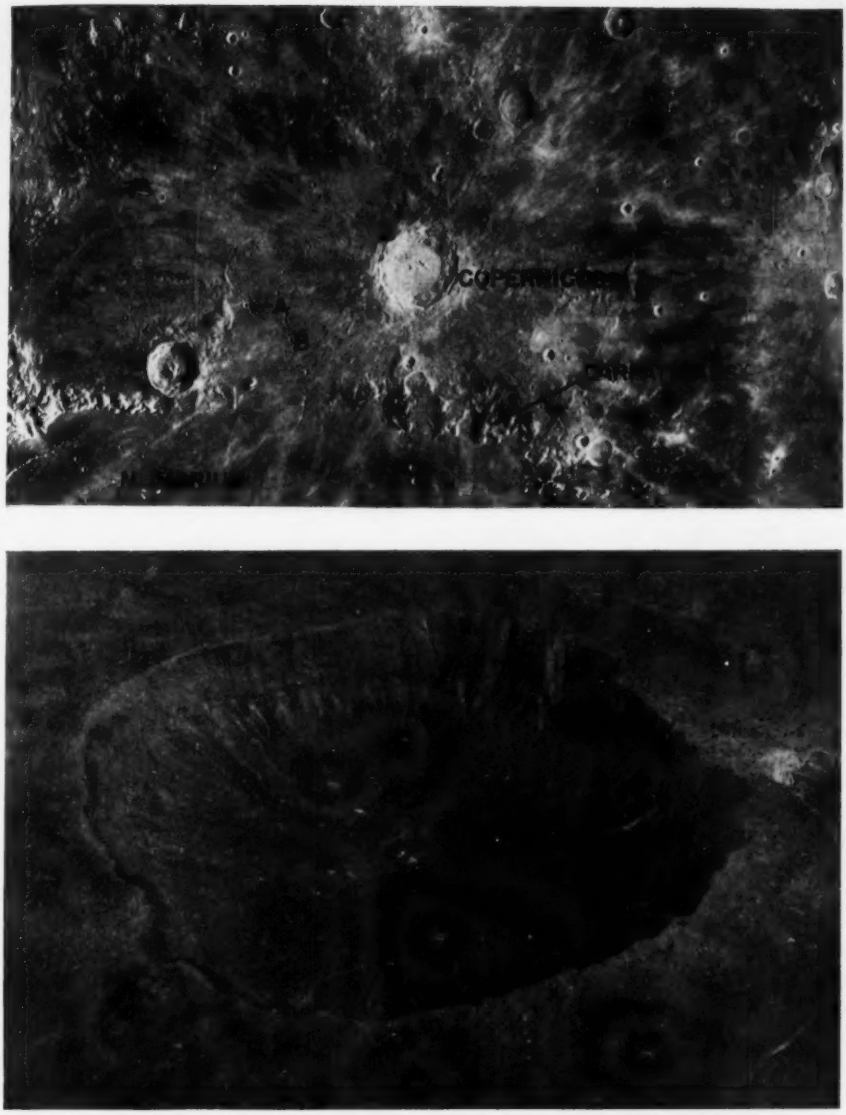


FIG. 4.—*Above:* Copernicus and vicinity. Copernicus is a youthful, medium-sized crater (56 miles in diameter, 12,000 feet deep), with a well-developed ray system. The chain of pits marked *B* are, for the most part, not true craters, as can be observed by comparing them with the crater marked *A*. Note that the Carpathian Mountains are explosion-grooved and that these grooves converge toward the center of Mare Imbrium. Photograph by Mount Wilson Observatory. *Below:* Meteor Crater, Arizona. A terrestrial meteoroid impact crater formed in recent times. This crater is similar in most respects to the smaller lunar craters. Aerial photograph by the writer in 1944.

cient energy to raise the mass of material ejected from Meteor Crater, Arizona, to a height of 65 miles. Although much of the energy is actually used in other ways, it is clear that a relatively small body, compared with the diameter of the crater formed, could have produced this terrestrial crater.

Perhaps the enormous amount of energy contained in a meteorite can be better appreciated by comparing it with a high-speed bullet. A bullet traveling at a velocity of ½ mile per second produces a considerable amount of heat and semi-explosive effects upon impact. Yet, because the kinetic energy of a mass varies as the square of its velocity, a bullet traveling at the not uncommon meteoritic velocity of 40 miles per second would contain 6,400 times the amount of energy that it does at ½ mile per second. C. C. Wylie[6] states that a meteorite traveling at such a velocity contains more than three hundred times as much energy as an equal volume of nitroglycerin.

The explosive nature of the impact of a high-velocity and chemically stable body, such as a meteorite, is not generally appreciated by earth-dwellers because our atmosphere burns up nearly all incoming meteorites and decelerates most of those not so destroyed to speeds of only a fraction of a mile per second. In contrast, a hypothetical moon-dweller would be aware of the explosive nature of meteorites but might doubt that a high-velocity and chemically stable body, such as a meteorite, can burn brilliantly because, in the atmosphereless lunar environment, one would never see a "shooting star" and all meteorites would explode on the lithosphere. Although such a moon-dweller would never see a stone burn, earth-dwellers have recorded meteorite explosions, because at infrequent intervals a giant meteoroid plunges through the atmosphere and strikes the surface with a velocity of many miles per second. Such a giant meteoroid, with a mass of at least a thousand tons or more has a relatively small surface compared to its mass, so that it is not greatly retarded by the friction of the air. The Siberian fall in 1908[7] was accompanied by an explosion of sufficient magnitude to devastate a wooded and swampy area 50 miles in diameter, although only a few small circular craters formed, the largest 50 meters in diameter.

### SHAPE

Lunar craters do not closely resemble those produced by terrestrial volcanism, but they do resemble known terrestrial meteoroidal-impact craters, such as Meteor Crater, Arizona (Fig. 4). For example, in lunar craters: (1) the floors are depressed below the surrounding terrain; (2) the total volume of the material displaced and now present in the rims appears to be approximately equal to the volume of the cavity of the crater; (3) there are no unquestionable examples of associated lava flows; (4) they are not nested in mountain tops or other physiographic heights; (5) they have lipped rims; (6) they have a more or less constant depth-width ratio for a given type of crater; (7) the walls and rims of the craters are seldom breached; and (8) they have the appearance of being instantly and completely formed. This lack of similarity between lunar and terrestrial volcanic craters and calderas is appreciated by many who have sup-

[6] "On the Formation of Meteorite Craters," *Pop. Astr.*, Vol. XLI (1933), pp. 211–14.

[7] L. A. Kulik, "The Question of the Meteorite of June 30, 1908, in Central Siberia," *Pop. Astr.*, Vol. XLV (1937), pp. 561–62.

ported the hypothesis of lunar volcanism. They suggest that this may be due to peculiarities of the lunar environment. Yet there is nothing known about conditions on the moon which suggests that there might be such a great difference in shape between lunar and terrestrial features as there is in size. There are two shape characteristics of lunar craters: (1) their circularity and radial symmetry and (2) the central peaks, which have been frequently cited as evidence against the impact theory. These features are therefore selected for special analysis and interpretation.

Many selenographers have stated that the high radial symmetry and the circularity cannot be explained by impact, because few meteoroids would impinge normal to the moon's surface, while most would strike at oblique angles, producing oval craters. Early advocates of the impact theory attempted to account for the lack of oval craters by special postulates, such as having the angle of incidence controlled by lunar gravity or by having the oval craters spring back to a circular shape by elasticity. G. K. Gilbert[8] supposed that the missiles were part of a Saturn-like ring which revolved around the earth. On this basis he showed how a majority of the missiles would strike at a high angle of incidence. It is, however, unnecessary to postulate any special condition, because an explosion crater, in contrast to a percussion crater, has a circular shape and well-developed radial symmetry, regardless of the angle of incidence. Such an explosion crater may be somewhat modified by accompanying percussion effects; for example, a circular shape might be altered to a slightly oval shape and the radial symmetry altered to a slightly bilateral symmetry. Terrestrial craters, such as Meteor Crater in Arizona, the Siberian craters, the Estonian craters, the Wabar craters in Arabia, the Campo del Cielo craters in Argentina, the Henbury craters in Australia, and the Odessa crater in Texas, all of which are established as impact craters by the presence of associated meteoritic material, are quite circular in shape. Meteor Crater, Arizona, for example, is 3,800 × 4,000 feet, which is particularly significant, since there is evidence that the meteoroid approached at a low angle from the northwest.[9] All except a few of the thousands of meteorite fragments recovered have been found scattered around rather than in this crater, suggesting an explosion with almost complete destruction of the meteoroid. In contrast, terrestrial volcanic craters seldom exhibit the high symmetry and circularity apparent in lunar craters. Many volcanic explosions produce irregular-shaped cavities. Even calderas, such as Crater Lake, Oregon, which is considered to be a highly symmetrical caldera, is 6 miles long by 4 miles wide. Comparatively, volcanic explosions are probably of a low order, from a small area source, and in a series, so that the explosion cavities produced lack high symmetry.

Many lunar craters contain centrally located prominences, which, although never exceeding the outer rim in elevation, range up to over 5,000 feet in height. These prominences are most commonly present in the medium-sized craters, and they vary in shape from almost perfect domes to fluted pyramids and groups of separate, jagged peaks.

Although the mechanics of a meteorite-impact explosion and the resultant rock deformation are not well known, there is

[8] "The Moon's Face," *Bull. Phil. Soc. Wash.*, Vol. XII (1892), pp. 241–92.

[9] W. Goodacre, *The Moon* (Bournemouth, England: Pardy & Son, 1931), p. 29.

theoretical evidence to show that a crater with a central dome can be formed by such an explosion. A meteorite, when it strikes the moon's surface, is traveling many times faster than the shock waves it produces in rock, so that, initially, there is little pushing-aside of the material in front of the impinging body. Under this condition Boon and Albritton show[10] that, instead of deforming plastically, rock becomes highly compressed and then "backfires" elastically, with explosive violence. In this manner a damped-wave structure, consisting of a central dome with a surrounding ring graben, such as is characteristic of many lunar craters, might be produced by meteoroids, which would almost invariably strike at velocities greater than $2\frac{1}{2}$ miles per second, which is approximately the velocity of a shock wave in granite.

The lunar crater, Alpetragius (Fig. 2), 11,000 feet high, 26 miles in diameter, is an excellent example of a crater not modified by melting or erosion and therefore containing an almost perfect central dome. It is noteworthy that Alpetragius contains a dome rather than a cone, because, if this crater is an impact feature, a dome suggests a rebound structure, while a cone might suggest a huge "explosion cone" that had withstood the force of the explosion. The lack of a physiographically expressed dome in most of the smaller crater pits of the type to which Meteor Crater, Arizona, may be compared is possibly due to the small size and/or the low impact velocity of the impinging body. Although almost half of the medium-sized lunar craters contain central peaks, these prominences are rarely domical because sufficient superheated molten lava is generated to form a pool in the bottom of the crater and at least partially to melt the central dome and sap the outer wall. In this manner the central dome is undercut by melting, creating slides which modify its form to that of a fluted pyramid. If a large amount of molten lava is generated by the impact, as in the case of the large craters, the central dome may be reduced to a group of separate peaks or may be entirely destroyed, so that no indication of its ephemeral existence remains. Such an inner pool of lava also undercuts the outer wall, causing slides and slumps and producing the terraced or "wreath" structure exhibited by many craters, such as Copernicus. It is noteworthy that such craters as Alpetragius, which do not have their central dome modified by melting, also do not have a "wreathed" outer wall.

An objection to the above explanation for the central peaks is that there are no comparable terrestrial structures of proved impact origin. There are, however, many geological explosion structures characterized by a central uplift, which have been ascribed to deep-seated and "muffled" volcanic explosions[11] but which may actually have been produced by meteoritic impact.[12] Recently formed impact craters, such as Meteor Crater, Arizona, are probably not of sufficient size to exhibit a physiographically expressed dome.

Proponents of lunar volcanism might explain the central peaks as solidified plugs of lava pushed out of a volcano vent by subterranean pressure. For this

[10] J. D. Boon and C. C. Albritton, Jr., "Meteorite Scars in Ancient Rocks," *Field and Laboratory*, Vol. V (1937), pp. 53–64.

[11] W. H. Bucher, "Cryptovolcanic Structures in the United States," *16th Internat. Geol. Cong. Rept.* (1933), pp. 1066–70.

[12] J. D. Boon and C. C. Albritton, Jr., "Meteorite Craters and Their Possible Relationships to 'Cryptovolcanic Structures,'" *Field and Laboratory*, Vol. V (1936), pp. 1–9.

type of phenomenon there is a well-known geological precedent. Mount Pelée in Martinique thrust up above the top of the crater an obelisk-like spine to a height of over 1,000 feet, but this was soon destroyed by crumbling. A second possibility is that these central prominences are parasitic cones. Third, certain domes, such as the dome in Alpetragius, might be laccolithic in nature. Fourth, these central cones might be formed by crypto-volcanism, i.e., a deep-seated "muffled" explosion of gases derived from magmas. Such an explosion might be too weak and unconcentrated to blow out a crater but sufficiently strong to dome the surface rocks. Yet, any hypothesis involving volcanism does not adequately explain (1) why these peaks are invariably located in craters and in the central position and (2) why the crest of such a peak is invariably well below the rim height. Also, these various hypotheses involve rather complicated, and in some cases illogical, sequences of events.

As evidence for lunar volcanism, some selenographers have stated that a few of these central peaks contain craterlets nested in their summits.[13] The present writer has not been able to identify any unquestionable examples of such hilltop craterlets. A few craters, such as Timocharis, under the condition of lighting in Figure 3, appear to contain such a hilltop craterlet. Yet, if one examines a photograph of this same feature with the light falling from the opposite direction,[14] no craterlet is seen, so that the supposed crater may be the shadow cast by an isolated peak. Certain other central prominences appear to have a group of isolated peaks with a saddle or possibly a slight depression or "pseudo-crater," which might be misinterpreted as a true crater. The absence of these hilltop craterlets is obviously predicted by the impact theory, except for the occasional chance hit of a second small meteorite on the top of a central prominence. However, if the proponent of lunar volcanism claims that true hilltop craterlets are common, he should explain how they were formed, because other types of lunar craters are not nested in peaks, as is the habit of terrestrial volcanic craters.

[13] See ftn. 9.

[14] N. S. Shaler, "A Comparison of the Features of the Earth and the Moon," *Smithsonian Contr. to Knowledge*, Vol. XXXIV (1903), Pl. XXI.

### DISTRIBUTION

Lunar craters are many times more abundant on the terrae than on the maria because, as is shown below, the maria were formed relatively late in lunar history. If one allows for this fact, it is apparent that the craters are scattered at random. Such a scattered distribution is in accord with the impact theory, since the point at which a meteorite strikes the moon's surface is controlled largely by random probability. Volcanic features, on the other hand, should be developed along fault lines or other lines of tectonic weakness. The lack of any apparent tendency of the great majority of craters to show any linear arrangement is, therefore, significant evidence against lunar volcanism.

There are a few examples of linear arrangement of small crater-like pits, such as those in the vicinity of Copernicus, which are too well oriented to be the result of random impact (Fig. 4). The pits near Copernicus are not of impact origin, for they differ markedly from typical craters of similar size in that (1) they are not lipped and (2) they are oval and elongated, grading into trench-shaped grooves. Among these

pits there are a few true craters which can readily be identified by their symmetry or by examining this area on a photograph with "overhead" lighting, in which case the true craters show up as white spots and the pits disappear. One possible explanation of the pits is that they are the result of collapse of a lava tunnel or similar subterranean void formed by contraction as the subsurface lava of the maria cooled after the outer skin of lava had solidified. Also, there may be some relation of these pits to the serpentine ridge which extends from this region northward into Mare Imbrium. The formation of these pits may have been caused by collapse following the moonquake associated with the explosive formation of Copernicus.

There are a few linear chains of small true craters on Terra Australis, such as a row extending to the west from the south rim of the crater Ptolemaeus (Fig. 2). Such a line of small craters might be explained by the impact of a meteorite traveling tangentially to the moon's surface. Upon initial grazing contact, such a body might shear into a number of fragments, each of which would then impinge and explode separately. An alternate possibility is that such a string of craters was formed by a group of meteors, traveling in a swarm as in a comet's head, which impinged tangentially.

### PHYSIOGRAPHIC AGE OF LUNAR CRATERS

An examination of the lunar surface shows that different craters are in various stages of erosion. In fact, the terms "youthful," "mature," and "old-age" may be conveniently applied to these craters in much the same manner as they are applied to terrestrial physiographic features. Craters of the same physiographic age were not necessarily formed contemporaneously, for some may have passed through the stages more rapidly than others.

Youthful craters, such as Copernicus and Tycho, have (1) high angles of slope, (2) few superimposed craters, (3) unscarred walls, and (4) sharp outlines. Craters in early youth may be readily identified both on the maria and on the terrae when examined under conditions of "overhead" lighting, for the large craters in early youth are marked by a ray system, while the small craters are marked by a bright halo, often exhibiting "asterism," i.e., a miniature ray system. Youthful craters are present on the maria and on the terrae in about equal numbers.

Mature craters are most common and are largely confined to the terrae. Mature craters are characterized by (1) a moderate angle of slope, (2) a moderate number of superimposed craters, (3) a moderately sharp outline, and (4) a moderately scarred appearance. Clavius (Fig. 2) is an excellent example of such a mature crater.

Old age craters, such as Regiomontanus and the large unnamed walled plain immediately to the southeast (Fig. 2), are confined to the terrae or are formed by inundation by maria lava. These craters are typified by (1) a low angle of slope, (2) many superimposed craters or lava inundation, (3) an indistinct outline, and (4) a highly scarred appearance.

A popular version of the volcanic theory is that all the lunar craters were formed many eras ago by some type of bubbling or widespread volcanism when the moon was in a semimolten state, so that the present surface of the moon is the original crust. Yet the youthfulness of some craters, such as Tycho, suggests that they have been formed in relatively recent geological time, probably in the

Cenozoic. As lunar erosion is extremely slow, the elapsed time between the formation of the youngest and the oldest craters may be one or more geologic eras. It is likely that crater formation has been a continuous process, which is still taking place at infrequent intervals when large meteorites strike the moon. If the moon did cool from a molten state, the original crust probably has been so altered by later crater formation that, as is the case with the earth, an original crust is nowhere exposed.

### CRATER RAYS

Radiating from the most youthful craters are light-colored streaks or rays, which are best displayed under high incidence of sunlight. These rays are well displayed by such craters as Copernicus, Kepler, Byrgius, Anaxagoras, Olbers, Aristarchus, and Tycho. Some of the streaks extend to distances of almost 2,000 miles from the craters. As the rays cast no shadows and as they pass indiscriminately and without interruption over all terrain features, they are apparently thin surficial deposits of material blasted out of the lunar craters from which they radiate. Corresponding to the large ray systems are bright halos of small youthful crater pits, which display some "asterism," forming a miniature ray system. Owing to the low force of lunar gravity, the lack of an atmosphere, and the high curvature of the moon's surface, the great length of the rays can be accounted for by ejection velocities of only a fraction of a mile per second, because ejected fragments will travel from twenty-five to forty times as far on the moon as on the earth. Although the rays indicate an explosive origin for the lunar craters, ejection velocities, produced either by volcanism or by meteorite impact, would probably be sufficiently great to account for the rays.

As the lunar rays are associated with all the most youthful craters, probably all originally possessed a ray system, which, with the passage of time, was covered with rock or cosmic dust, or destroyed in some other manner. The nature of the highly reflecting material forming the rays is problematical, but it may be finely pulverized rock, meteoritic fragments, and solidified, recrystallized, or glassy material ejected in the molten state. Perhaps tektites are such material which was ejected at a velocity greater than 1½ miles per second, so that it left the moon's gravitational sphere and fell to the earth. Tektites contain lechatelierite or fused quartz, which requires too high a formation temperature to be a product of volcanism, although such material is produced by meteorite impacts.

### MARIA

The dark-gray lunar plains or maria, nearly all of which are interconnected, cover about one-half of the visible surface of the moon. If maria are present on the far side of the moon, they are not connected with those visible to the terrestrial observer, for the well-developed maria do not extend beyond the limb. These dark-gray plains lie at topographically lower levels than the terrae, so that, if a hypothetical hydrosphere were poured upon the moon, the water would cover at least a large part of the maria surfaces before beginning to inundate the terrae. Although there is no general agreement concerning the origin of these dark-gray plains, they have been almost universally interpreted as extensive solidified lava fields. The surfaces of the maria are relatively smooth and featureless and are sprinkled with comparative-

ly few craters; with numerous long, narrow crevices or rills; and with long, winding ridges of low relief. Inasmuch as the opposing walls of the rills show no evidence of vertical offset or of horizontal displacement, these features are probably not faults but possibly are crevices produced by contraction accompanying the cooling of the lava. A probable explanation for the long, narrow, winding, and branching ridges is that they are pressure ridges formed in the later stages of the cooling of the maria by the movements of subsurface fluid lava after the surface had cooled to a viscous or semisolid state. Inasmuch as the superimposed craters are all youthful and the maria inundate the physiographic features of the terrae both along the "shores" and in the central areas of some maria, such as Mare Nubium, it is apparent that the maria were formed late in lunar history.

The lava of the maria was apparently originally heated well above the temperature necessary to melt the rock of which the lava is composed. This superheated condition is evident, since the lava melted many of the features of the terrae with which it came in contact and since it was highly fluid, for it spread out over large areas, forming smooth plains. The formation of a superheated lava can be readily accounted for only by the impact of a large meteorite which would contain sufficient kinetic energy to change a large mass of solid rock almost instantaneously to superheated molten lava. In contrast, volcanic lava characteristically remains at relatively low temperatures near the solidifying point and is, therefore, incapable of accomplishing a significant amount of melting of the surface rocks with which it comes in contact. Such low temperatures are normal, since volcanic lava is not formed instantaneously but rather slowly in a subterranean reservoir, where stoping and melting of the walls of the reservoir prevent superheating.

If one accepts the impact origin of the lunar craters as presented above, the impact origin of the maria follows logically, for there is no great difference between some of the larger lunar craters, such as Calvius and Schickard, and some of the smaller maria, such as Mare Crisium. Of course, the meteoroids that formed the maria must have been extremely large, probably having asteroidal dimensions of many tens of miles. Although the maria retain only such characteristics of the craters as circularity and a depressed floor, the difference between the maria and the large craters becomes understandable if one extends one step further the changing aspects of the crater family beyond the large walled plain. In the crater series the variation of form with size is probably primarily due to the increasingly important role played by the molten rock, formed upon impact. Thus, small crater pits are unmodified by melting, and the medium-sized craters are only moderately modified by melting, whereas the formation of the large walled plains was accompanied by sufficient melting to destroy the central peak, wreath the outer wall, and partially fill the crater with a lava pool, decreasing the depth-width ratio. It is not surprising, therefore, that the primary effect of the impact of a meteoroid much larger than that which produced the walled plains is the generation of a large quantity of extremely hot lava. In fact, in the formation of the maria, sufficient lava has been generated to destroy or submerge the central dome and to breach and partially destroy the

surrounding wall, thereby flowing out over other parts of the lunar surface.

The most convincing evidence of the impact origin of the maria is found in Mare Imbrium (Fig. 3), a nearly circular area about 750 miles in maximum diameter, with a surface area of about half-a-million square miles. Mare Imbrium is bounded on three sides by mountain ranges, which have peaks ranging from 5,000 to 20,000 feet, named, beginning with the range immediately north of Copernicus, the lunar Carpathians, the lunar Apennines, the lunar Caucasus, and the lunar Alps. One encounters difficulty in attempting to explain these ranges by any process of mountain formation used to explain terrestrial mountains. The general shape of these features precludes the possibility that they were formed by folding, by volcanism, or by erosion. It has been suggested that these ranges are tilted fault-blocks and that the steep fronts facing the maria are fault scarps,[15] but according to such an explanation one would expect the dip slope to be a mature or old age surface, covered with numerous craters and other features. Actually, the dip slope appears to be a mass of rubble, with a few superimposed youthful craters, formed later than the mountains. Useful for comparison are the lunar Altai Mountains (Fig. 1), which appear to have formed by foundering along a fault zone. The terrain on both sides of the Altai scarp is an old age surface.

A reasonable explanation for the mountain ranges around Mare Imbrium is that they are of catastrophic origin and originated in a manner comparable to the ring mountains of the craters, by the impact explosion that formed Mare Imbrium. These mountains without "roots" originally may have encircled the maria more completely before they were partially destroyed by melting. They appear to be superimposed upon a structural ring arch, which forms a semicircle around Mare Imbrium (Fig. 3). This ring arch is physiographically evident because it is followed by a ring syncline into which lava has flowed, forming maria regions. These ring structures may be outer rings of the "damped-wave" impact structure associated with a meteorite impact.[16]

The vast amount of lava generated by the Imbrium impact, and possibly added to by lava released from the moon's interior, was apparently sufficient to breach the walls of the maria, so that it flowed out over other parts of the lunar surface, inundating the terrae and resurfacing some of the older maria scars. Mare Nubium, in particular, appears to have been formed by inflowing lava, because this region is not circular in shape and has only a thin skin of lava that partially covers the underlying terra surface. The excellently developed ray systems in this region may be explained by postmaria impacts, which have pierced the thin lava skin and exploded in the underlying and lighter-colored terra.

Further proof of the explosive origin of Mare Imbrium is in the lunar valleys and the "grooves" or "striations" which diverge from the center of this mare for many hundreds of miles. These valleys are well developed in the lunar mountains surrounding Mare Imbrium, while the "striations" and "grooves," although everywhere present around the mare, can be best seen in the central part of the moon (Fig. 1). These features cannot be faults, for in many cases they pierce both

[15] R. T. Chamberlin, "The Moon's Lack of Folded Ranges," *Jour. Geol.*, Vol. LIII, No. 6 (1945), pp. 361–73.

[16] See ftn. 10.

the northeast and the southwest rims of a crater without disturbing its bottom; therefore, these features must be surficial scars, probably formed by large missiles exploded out of Mare Imbrium. Because of the pulverized nature and the light weight of lunar rocks, these missiles had sufficient cohesive strength to plow and furrow the surface. There is evidence that these "striations" are not of meteoritic origin, for the missiles which formed them had a velocity low enough to produce percussion, rather than explosion, features.

Certain other maria, such as Mare Serentatis and Mare Crisium, have circular shapes and probably a thick layer of lava, suggesting that they are also impact scars rather than formed of lava from the Imbrium impact. Since all the maria surfaces are of approximately the same physiographic age, the maria must be approximately contemporaneous in origin, or the maria surfaces must have been reflooded with a new layer of lava from Mare Imbrium. The lack of a mountain ring of detritus around these other maria and the fact that the "shores" of these maria inundate old age terrae surfaces may be accounted for by complete destruction of such a mountain ring soon after formation by the lava of the maria. Since the centers of Mare Imbrium, Mare Serentatis, and Mare Crisium form a straight line, trending east to west, there may have been a triple impact of the Mare Imbrium body and two secondary "satellites," all three revolving in the plane of the ecliptic. The remaining maria can be largely accounted for by overflow of lava from these three maria.

## VOLCANISM AND LUNAR ENVIRONMENT

Aside from the lack of volcanic features in the present moonscape, the moon's surface lacks features resulting from the large-scale folding, faulting, and intrusive activity which indicate crustal instability and usually accompany volcanism. A consideration of lunar "geophysics" suggests that extensive volcanism is not likely on the moon and similar small celestial bodies except in the early youth of a body cooling from a molten mass.

The lunar surface lacks large-scale folding, although orogenic folding should be plainly visible if present. There is some evidence of ring arching associated with Mare Imbrium, and there was some folding associated with crater formation; but there is no counterpart of terrestrial geosynclines, geanticlines, or folded ranges. The only clearly apparent folded features on the moon are the ridges on the maria, which are, presumably, formed by lava flowage rather than by internal compressive stresses. If compressive forces acted on the moon's surface with the equivalent force and effect with which they have acted on the earth's surface, one might expect folded lunar mountains many times higher than terrestrial mountains because of the low lunar gravity and the slowness of erosion. Perhaps folding is not to be expected on the moon, for it is normally produced below the surface under high compressional loads. Such folding is not evident until the folded area is uplifted and exposed by erosion. Since lunar rocks have a low weight, one may predict that the lunar zone of fracture, in which faulting tends to dominate over folding, would be about ten times as thick as that of the earth.

The moonscape is probably highly shattered and complexly faulted, because there must be many faults produced by the explosions which formed the craters and the maria, including ring

faulting, ring landslip faulting, and radial faulting. However, although small forces would produce large displacements on the moon, there is no evidence of large master-faults or shear zones, such as are present on the earth. The rills and the valleys are probably not of fault origin. The lunar feature named the Straight Wall (Fig. 2), 70 miles long, 500–1,000 feet high, is, however, one unquestionable example of a lunar fault. Such a fault is not necessarily produced by internal stresses, since it can result from moonquakes accompanying meteoritic impacts. The scarp which forms the west-facing wall of the Altai Mountains may possibly be a fault scarp, although the nature of this scarp is problematical. Altogether, there is little evidence of folding or faulting of a nature to indicate internal instability, such as might be directly or indirectly associated with volcanism.

An examination of the moonscape also fails to reveal any evidence of intrusive igneous activity, although such activity is almost invariably associated with volcanism. For example, there are few features on the moon which can be interpreted as batholiths, stocks, laccoliths, sills, or dikes. The high symmetry of the lunar craters indicates the homogeneous nature of the lunar surface and suggests the absence of buried intrusive bodies.

It is necessary to tread on unknown ground even to hazard a guess about the past or the present internal condition of the moon; for this requires a knowledge of the age of the moon as a celestial body and a knowledge as to whether it cooled from a molten state, grew by cold accretion, or was torn from the earth. However, a small celestial body, such as the moon, would cool internally and probably become inactive diastrophically in a small fraction of the time required for a larger celestial body, such as the earth; therefore, if the moon is even of a moderate age compared to the earth, it is probably internally cold and inactive. Yet many lunar craters are physiographically in early youth, indicating that they are of geologically recent age.

Although the absence of a lunar hydrosphere does not make volcanism impossible, this lack of water other than juvenile is unfavorable to the formation of volcanic explosive features, since water serves as a flux which lowers the temperature at which rocks liquefy and is the primary explosive agent of volcanism.

Planets of the solar system furnish evidence that the strength of the crust of a celestial body has an inverse relation to the mass. Therefore, it can be predicted that our satellite, because of its small mass and low specific gravity, has a strong crust and is not subject to such plastic deformation as is the earth. Also, owing to the mass and specific gravity of the moon, the internal pressure at its center is equivalent to the pressure at a depth of only about 100 miles in the earth's crust. Both of these conditions are unfavorable to the development of volcanism.

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# LATE-GLACIAL AND POSTGLACIAL CHRONOLOGY ON ADAK

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ABSTRACT

A late-glacial and postglacial chronology on Adak Island in the Aleutian chain is represented by a series of three wind-blown sands, each terminated by a soil zone, and all three overlying a slightly weathered late-glacial till and marine terrace. Evidence of human occupation is present in the soil zones of the two upper sands. The younger culture is recent Aleut, the older is unidentified. It is suspected that the chronology results from variations in climate obtaining over a large portion of the North Pacific.

## INTRODUCTION

The island of Adak is situated midway along the Aleutian chain and is one of the Andreanof group (see Fig. 1). It is a mountainous island of approximately 275 square miles, with deep bays and re-entrants which give its coastline a length of about 2,000 miles. It is 28 miles long in a NNE-SSW direction and has a maximum width of 18 miles. The highest summits are Mount Moffett, at the northern end of the island, and an unnamed height in the southwestern portion of the island, with altitudes of 3,876 feet and 2,249 feet, respectively. The island is composed of intrusive and extrusive igneous rocks. Volcanism has progressed from south to north on Adak, a process noted as characteristic of many of the Aleutian Islands.[1] Mount Moffett and Mount Adagadak, both extinct volcanoes, represent the latest and most northerly expressions of this activity on Adak. Glaciers once existed on the island. Although the higher peaks and ridges were probably ice free during maximum glaciation, alpine glaciers united to form piedmont glaciers, which covered a large portion of the island.

The northern part of the island, with which this report deals, is essentially a peninsula (Fig. 1). Mount Moffett forms its northwestern extremity and is connected to the main portion of the island to the south by a ridge averaging 400 feet in altitude but reaching a little over 600 feet at two points. Mount Adagadak, with an altitude of 2,115 feet, forms the northernmost headland and is nearly cut off from the rest of the island by a lowland, much of which is occupied by Clam and Andrew lagoons.

The investigations here recorded are concerned with the wind-blown sands which have collected behind the beaches of Kuluk Bay and in the vicinity of Clam Lagoon, as shown in Figure 1. They were made during 1944, while the author was serving with the United States Navy.

## WINDS AND SOURCE OF SANDS

Aerial photographs taken during the occupation of Adak by the armed forces of the United States indicate that the most recent dune pattern along the western shore of Kuluk Bay has resulted from winds moving from the northeast and east. The winds now eroding the Clam Lagoon dunes are also predominately from the northeast quadrant, although cutting is also accomplished by winds from the southwest.

Sands in the dunes consist chiefly of

[1] S. R. Capps. "Notes on the Geology of the Alaskan Peninsula and Aleutian Islands," *U.S. Geol. Surv., Bull. 857-D* (1934), p. 145.

feldspar and ferromagnesium minerals derived by wave or glacial action from the local bedrock. Comparatively little quartz is present. The sand has been blown inland from the beaches and deposited along the low coastal area fringing the northwestern portion of the island. As the winds moved southward and westward up into the hilly country of the island or spent their energy within the Kuluk Bay area, which is surrounded by high country on almost all sides, sand was deposited. Obviously, migration inland from the beach would be promoted by strong northeast winds, large supplies of sand, and decreased obstruction by vegetation.

## CLIMATE

Weather records in the Aleutians are scattered and incomplete. Adak and the other islands in the chain enjoy a mild, temperate climate with abundant rainfall and relatively mild summers and winters. Although the available records on Adak cover only parts of two years, the island's weather appears to duplicate that to both the east and the west along the chain. The mean annual temperature is 39.7° F. The maximum mean annual temperature is 43° F. and minimum, 36.4° F. A full-year precipitation record is not available, but the annual precipitation probably approaches 60 inches. The prevailing winds are from the southwest and average 15 m.p.h. During the months of November, December, January, March, May, and June, however, prevailing winds are from the north and northeast.

## VEGETATION

The vegetation of Adak has not been adequately studied and described. However, the writer's observations indicate that the island supports two general types of vegetation. The first is restricted to sand-dune areas near the shore. The second, which is by far the most extensive, covers the upland areas. No trees are indigenous to Adak or to the other Aleutian Islands.

The present surface of the dunes is covered with a hearty, well-rooted vegetation consisting of grasses, wild grains,

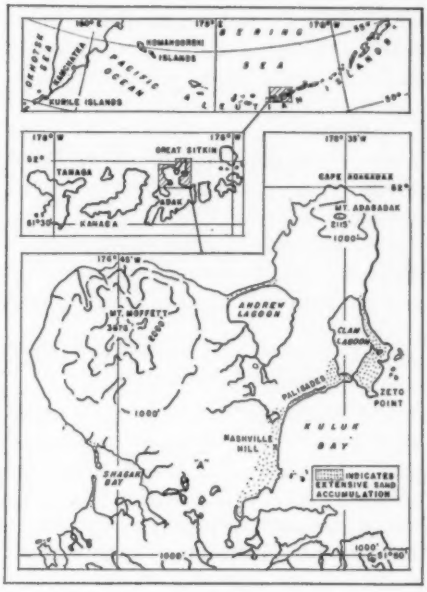


FIG. 1.—Index map

tuberous-rooted plants, and numerous species of flowers. The uplands are characterized by what may be termed a "dry tundra." This association includes large amounts of heather, blueberry, and grasses, with occasional ground willow, and a great variety of flowers which bloom in profusion during the short summers.

Thin deposits of sand, on slopes inland from the extensive dune accumulation along the beaches, indicate that the area was not bare of vegetation during periods

of sand accumulation. Sand was deposited in spite of a vegetative cover and in a form at least partially modified by it.

### OTHER AREAS OF SAND ACCUMULATION

The Adak sands are not unique since areas of stabilized dunes are known to exist on other islands of the Aleutian chain. To the west of the Aleutians similar deposits are located in the northern Kurile Islands and on southern Kamchatka. The dunes are for the most part stable. In those places where erosion is now proceeding the process can usually be ascribed to man's activity. In a few instances instability can be attributed to strong wind and wave action. Aerial photographs reveal that in many places the abandoned villages of the recent Aleut or closely contemporaneous peoples are located in areas of stable dunes.

### DESCRIPTION OF DEPOSITS OF WIND-BLOWN SANDS

The best single exposure in the sand-dune area of Adak is an 80-foot cliff of sand, till, and weathered bedrock on the northwest shore of Kuluk Bay where the sand dunes and the beach give way to the bedrock of the Palisades (Fig. 2). Brecciated bedrock, perhaps largely frost-riven, grades upward into 10 to 15 feet of bedrock in which the minerals are chemically decomposed. This is unconformably overlain by 4 to 5 feet of fresh gray till, slightly weathered at its upper limit. Over this lies the reddish soil of the oldest wind-blown sand. The soil carries stringers of white pumice, characterized by pellets averaging approximately $\frac{1}{4}$ inch in diameter. The pellets are composed of finely vesicular glass with small crystals of hornblende, small fragments of plagioclase (labradorite), and some biotite. There follows a second wind-blown sand, capped by its soil zone and overlain in turn by a third layer of wind-blown sand and soil zone. This last soil is the present surface of the stabilized dunes. The thickness of the section from brecciated bedrock to the ground surface is approximately 35 to 40 feet. The lower 40 feet of the 80-foot cliff is obscured by slump. Immediately to the south, till and bedrock are no longer exposed, and the three sands and their soils occupy a section of nearly 75 feet from beach to modern soil. The lowest sand and soil can be followed to the south for about 300 feet while the upper sands crop out almost uninterruptedly for $\frac{1}{2}$ mile in the same direction.

Aside from stratigraphic relationships, there is no apparent field distinction between the three wind-blown sands in their unweathered state. All are gray in color and of uniform consistency.

The thickness of each of the three soils ranges from 2 to 5 feet. They are all sharply defined at their upper limit and all grade downward into the sand from which they were formed. They differ, however, in their development. The two lower soils are marked by a "B" zone consisting of an accumulation of iron oxide which gives the sand a red color. This accumulation in the lowest soil is so great and cements the sand grains so completely as to form local bodies of "ironstone." The "A" zone, where present, is characterized by small amounts of humic material. The formation of both the lower soils was interrupted by the addition of small amounts of blown sand to the surface. The topmost sand is immature in comparison with the other two. Little iron oxide has accumulated in the "B" horizon, and the "A" horizon is made up of gray humic beds with intervening stringers of light-colored sand blown in during the process of soil formation. Volcanic ash further aids in dis-

tinguishing among the soils. The lowest soil carries lenses of pumice, and the youngest includes stringers of yellowish silt of high volcanic-ash content. No ash was noted in the middle soil.

Midway along the western shore of Kuluk Bay, a mile south of the above-described exposure, the sands are again well exposed. Here the sands have accumulated around the western and northern flanks of Nashville Hill, a plug of porphyritic granodiorite. The till is missequence on the slopes of Nashville Hill are shown in Figure 5.

On the south side of Clam Lagoon, at the north side of Kuluk Bay, an extensive sand-dune area is now undergoing rapid wind erosion. The erosion of the Clam Lagoon dunes is believed to have commenced prior to the occupation of Adak by military forces in 1942. Sand is being deposited in Kuluk Bay, and considerable shoals already exist. In the "blowouts" the soil zone of the second or

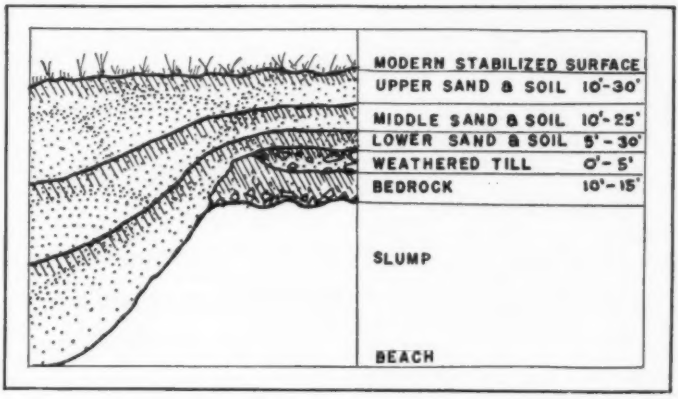


FIG. 2.—Generalized section at west end of Palisades

ing, and the sand series rests on beach deposits which form a marine terrace approximately 10 feet above high-water mark. The soil of the lowest sand, carrying the stringers of pumice, is discontinuous, but the middle and upper sands with accompanying soils are well exposed, as shown diagrammatically in Figure 3. The photograph of Figure 4 shows the soil of the middle sand overlain by the most recent sand and its soil zone. Higher on the slopes of Nashville Hill the sand cover on bedrock thins, and in road cuts the entire sequence of three sands and corresponding soils is only 5 feet thick. The relationships of the beach dunes, elevated beach deposits, and the middle sand has been truncated. The photograph reproduced in Figure 6 shows a pattern, roughly that of a figure eight, resulting from the removal of the upper sand and the beveling of the middle sand and soil. Figure 7 shows the trace of the soil zone of the middle sand along a cut in the dunes, with the youngest sand on top and the middle sand below. At this place the lowest sand and soil were not identified nor was any till found. There is, however, a low terrace around the western and southern sides of Clam Lagoon. Its surface is approximately 10 feet above high water, and the sand deposits appear to rest on it. It is correlative with the elevated and sand-

covered beach gravels noted at Nashville Hill. Its surface was formed at a slightly higher stand of sea-level and before the bar connecting Zeto Point with Mount Adagadak was built to form the eastern shore of the lagoon.

The till and sand-soil sequence is also developed away from the beach dune area in the hills of the northern part of the island. Near the Shagak Bay–Kuluk Bay divide and between the mountainous country to the south and Mount Moffett to the north (Point *A*, Fig. 1), overburden in a quarry cut illustrates the sequence. Above deeply weathered bedrock the section is approximately 5 feet thick. Till 12 to 18 inches thick is slightly weathered at its upper limit. The till is followed by some 12 inches of sand and silt in the top of which is developed a soil covered by a thin bed of pellet ash. Sand, silt, and clay, a foot thick, merge upward into discontinuous humic beds, also capped by a thin bed of pumice pellets. The upper foot is a soil zone of humified sand and silt to the present surface. The upper and lower sands with accompanying soils are recognized, but the middle sand is not definitely identified.

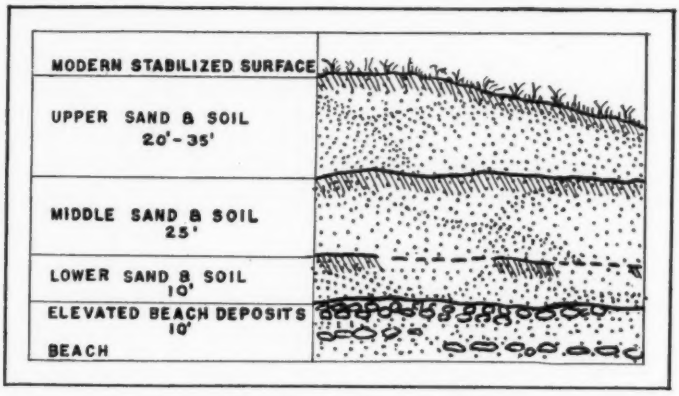


FIG. 3.—Generalized section at Nashville Hill

### POLLEN AND DIATOMS OF THE SOILS

Small lenses of peat are present in the soils developed on the three sands. Analyses of the pollen and diatoms contained in random samples of these peats have been made by Arthur S. Knox of the United States Geological Survey. His results are presented in Table 1.

The conclusions from the analyses are limited for several reasons. In the first place, a total of only five samples from the three soils was available for analysis. They may not have been representative of all the Adak peats. Assuming, however, an adequate and representative collection, the use of pollen analysis in the development of a geochronology in the Aleutians is, at present, restricted by other factors. The first of these is that modern vegetation of the area is not well enough known to provide a point of departure in the reconstruction of relative climatic variations of the past. Second, pollen analysis usually relies upon the use of the tree pollen and this will undoubtedly be lacking in most Aleutian peats. Third, no pollen analysis has been previously made in the Aleutians and certainly no general conclusions as to past climates of a large area can be ex-

trapolated from the geographic pin point represented by the present analyses.

In spite of the above restrictions on the use of pollen, it can be pointed out that the absence of tree pollen in the samples indicates that conditions during peat development were no more favorable for tree growth than they are at the present. Knox reports that, although he examined several thousand pollen grains from the samples in addition to those listed in Table 1, the only conifer pollen encountered was a single grain comparable in appearance to *Pinus banksiana*, or scrub pine of the north. This grain was, he writes, "in poor condition and appears to have been transported by wind a considerable distance."

The greatest differences in pollen and diatom content are noted between the topmost soil, on the one hand, and the middle and lowest soils, on the other. Knox refers to peats therein as "fern-sedge peat" and "sphagnum moss peat," respectively. The following conclusions from these differences are quoted from Knox: "The presence of fungi and the lack of sphagnum and diatoms indicate dryer conditions during the development of this layer [peat of topmost soil] than of the others [peats of middle and lowest soils]. The large number and variety of herbaceous plants, as indicated by their pollen, suggest favorable conditions for their growth probably including a

FIG. 4.—Middle sand and soil overlain by upper sand and soil at Nashville Hill.

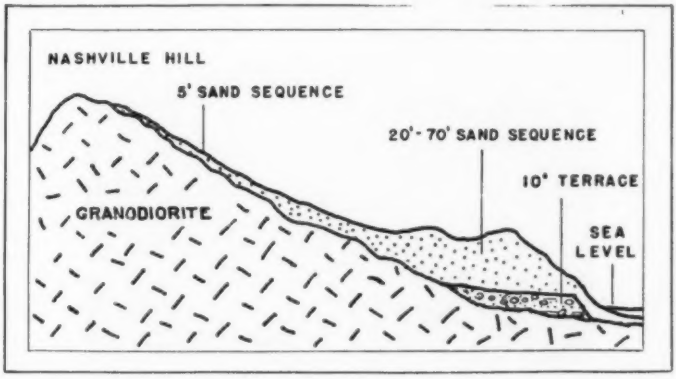


FIG. 5.—Generalized section through Nashville Hill showing relation of the sequence of sand, marine terrace, and bedrock.

warmer climate than during the formation of the other soils."

Knox is unable to state whether the peat of the topmost soil represents a climate warmer than the present. The position of the peat, however, in the horizon of the recent Aleut and close to the modern surface in a soil of accumulation indicates a small time interval between its formation and the present. This would suggest a climate nearly comparable with the present. In turn it might then be said that the two lowest soils were formed under conditions slightly cooler and moister than the present.

FIG. 6.—Figure-eight pattern resulting from beveling of upper sand and middle sand and soil in Clam Lagoon blowout.

It is unfortunate that there is no information available on the pollen content, if any, of the sands between the soils. The profile is thus interrupted, and we have no indication from this source of the relative nature of the climate intervening between the soils.

### ARCHEOLOGY OF THE SANDS

Evidence of human occupation was found in two horizons of the post-till deposits. The soil developed on the latest blown sand carries the artifacts, burials, kitchen middens, and barabaras of the Aleut. Remains are plentiful throughout the sand area and are often found immediately below the soil's yellow, clay-like zone and within a few inches of the modern surface.

FIG. 7.—Middle sand and soil overlain by upper sand and soil in Clam Lagoon blowout

Evidence of human occupation was also discovered in the next lowest soil, developed on the middle sands. Hearthstones, charcoal, worked flakes, and cores were found in this zone. No diagnostic artifacts could be assigned definitely to the middle soil, although several artifacts, closely associated with time in the Aleutian area, but, like the point in question, their stratigraphic position has not been clearly established.

## CHRONOLOGICAL EXTENT OF THE SEQUENCE

The freshness of the till, over which lies the sand-soil sequence, indicates that it, were found in the Clam Lagoon blowout. As they were not in place, however, they could also have been let down from the youngest soil. One diamond-shaped point, not generally characteristic of the Aleut points, was so found. Similar points have been found from time to it is probably Wisconsin, although it is impossible to assign it to a definite stage within the Wisconsin. A certain amount of time, as represented by the weathering of the till, elapsed prior to the deposition of the oldest sand. Whether, however, the sand-soil sequence represents all the

TABLE 1

DISTRIBUTION OF POLLEN, SPORES, AND DIATOMS IN THE THREE SOILS AS DETERMINED BY ARTHUR S. KNOX

| | TOPMOST SOIL* | MIDDLE SOIL† | LOWEST SOIL‡ |
|---|---|---|---|
| | Pollen and Spores§ | | |
| Fern spores | 44.1 | 1.2 | 3.0 |
| Sphagnum moss | .6 | 77.5 | 66.9 |
| Grass | 14.5 | 10.5 | 8.1 |
| Sedge | 5.5 | 5.7 | 10.6 |
| Heath | .3 | .3 | 1.8 |
| Willow | .9 | .1 | .7 |
| Equisetum | ..... | 2.0 | ..... |
| Lycopods | ..... | .4 | 2.5 |
| Other herbaceous plants | 33.2 | 2.6 | 8.2 |
| Fungi | Spores and other remains of fungi abundant | ..... | ..... |
| | Diatoms‖ | | |
| *Pinnularia dactylus* | ..... | frequent | frequent |
| *P. viridis* | ..... | frequent | frequent |
| *P. lata* | ..... | ..... | common |
| *Navicula semen* | ..... | ..... | frequent |
| *Diploneis* cf. *D. elliptica* | ..... | ..... | common |

* One sample, 342 spores and pollen counted.
† Two samples, 1,007 spores and pollen counted.
‡ Two samples, 759 spores and pollen counted.
§ Pollen analysis is given in percentage.
‖ Diatoms are listed according to relative frequency.

time from the till weathering to the present or whether gaps exist in the sequence is unknown.

### ORIGIN OF THE SEQUENCE

Glaciation of Adak and other islands of the Aleutian chain was local in the sense that it was mountain rather than continental glaciation. However, the present mild climate and low altitudes of the island indicate that such glaciation did not exist separately and apart from the major ice advances on the continents. It is felt that the glacial climate represented by the Adak till and the milder postglacial climate represented by till weathering are reflections of, and synchronous with, similar climates obtaining over a large geographic area.

The causes for sand movement and subsequent stabilization following the till weathering are less clear. Formation of sand dunes depends upon the presence of sand, wind capable of moving it, and a place to deposit the sand moved. The stabilization of free sand depends upon the modification or absence of the factors which caused the original sand movement. The presence, modification, and absence of these factors may be either local or of a considerable geographic extent.

Sand supply appears to be the most critical of the three factors involved in this instance of sand-dune formation. Winds are now more than strong enough to move sand and in all probability were equally effective in the past, if not more so. A place to deposit sand has always been available. The supply of sand, however, is limited. It may be increased in two general ways. First, the vegetative cover may be destroyed, thus allowing the winds to remold the already existing dunes. Second, the now narrow beaches, behind which the dunes have collected, may be widened, thereby presenting a greater source area of sand to the transporting winds.

Three local causes may have contributed to the destruction of vegetation and opened old dunes to partial or complete re-working by the wind. They are volcanic activity, fire, and the activity of man and animal. Active volcanoes on Great Sitkin Island to the east and on Kanaga Island to the west may have given off enough ash at various times in the past to destroy the vegetative cover and start sand movement. Ash is found in the lowest soil, and smaller quantities are present in the topmost soil. In neither case, however, has soil development halted with the introduction of ash. These facts, combined with the absence of ash from the middle soil, tend to eliminate volcanic activity as a cause for the initiation of sand movement. No evidence of extensive burned areas was noted within any of the three soil zones. This, too, is discarded as a cause for sand movement. Evidence is lacking to indicate that excessive activity by either man or animal has ever sufficiently destroyed the vegetative cover to permit sand movement. Climatic fluctuation, a nonlocal cause, may be considered as having destroyed the plant mantle to such an extent that sand movement was initiated. Such a climatic shift would of necessity have been extremely violent, and probably only the most rigorous of glacial climates would have driven out all plant life. Moreover, it has already been pointed out that sand has accumulated in spite of the presence of vegetation.

There remains the possibility of widening the beaches to increase the supply of sand. This could be effected by relative movements of land or sea. Such movement could be due either to diastrophism or to eustatic changes in sea-level. The present seismic activity of the area may be offered in favor of land movement. The presence of the 10-foot marine terrace and of elevated beach deposits may also substantiate the theory. However, the complete sand-dune sequence cannot be ascribed to this single terrace; and, furthermore, this terrace may be due to eustatic changes in sea-level rather than to a rise of the land. It is also difficult to accept the theory of the rhythmic rise and fall of land necessary for the alternate exposures and submergences of the beaches demanded by the dune sequence.

Eustatic changes in sea-level to expose and cover the beaches are easier to accept as a premise. It could then be argued that ice accumulations elsewhere drew off enough water to widen the beaches and supply sand for the dunes. Slight ameliorations in climate would raise the water level sufficiently to reduce the sand supply and allow soil development. Although such a mechanism is favored here, the proof is not at hand. Other sand deposits in the North Pacific area must be examined before the contention can be substantiated or rejected.

Despite the belief that climate has played a major and deciding role in the sequence, no attempt has been made to correlate this sequence with known climatic variations of the late-glacial and postglacial in Europe, Asia, and North America. It is felt that the sequence is too isolated geographically to warrant so highly a speculative exercise as such an attempted correlation would demand.

## SUMMARY

A late-glacial and postglacial chronology exists on Adak. It is represented by a slightly weathered till, probably Wisconsin, and a marine terrace, followed by three wind-blown sands, each with a developed soil zone. It is suspected that this sequence in its entirety results from climatic fluctuations and is of general distribution throughout a considerable portion of the North Pacific, but lack of ground observations elsewhere in the area precludes a definite statement.

Remains of the recent Aleut are confined to the topmost soil developed on the latest blown sand. Evidence of human occupation in the soil of the second oldest sand presumably indicates either a pre-Aleut people or a somewhat greater antiquity for the Aleut than is usually ascribed to him.

Whether the chronology found on Adak has a wide geographic distribution and, if so, whether cultural remains older than the comparatively recent Aleut are present must be shown by investigations elsewhere in the North Pacific.

ACKNOWLEDGMENTS.—The artifacts found on Adak are now in the possession of the Smithsonian Institution and have been examined by Dr. Frank H. H. Roberts, Jr., and Dr. Henry B. Collins, Jr., of that institution. Mr. Arthur S. Knox, of the United States Geological Survey, has most generously provided of his time and knowledge to analyze the peat samples. The brief climatic data have been provided by the United States Army Air Forces. Thanks are extended to Professor Kirk Bryan of Harvard University, and to Mr. Charles E. Stearns, of Tufts College, for critical reading of this paper.

# FOSSILIFEROUS PEBBLES IN "PENSAUKEN GRAVEL" AT PRINCETON, NEW JERSEY

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ABSTRACT

Identification of fossils preserved in chert pebbles in the "Pensauken gravel" at Princeton, New Jersey, demonstrates that these pebbles came from Paleozoic rocks of northwestern New Jersey and adjacent parts of New York. They were presumably transported to Princeton by the Delaware River when it flowed, as postulated by Campbell and Bascom, across northwestern New Jersey on its way to Trenton. The fossils do not, however, support Campbell and Bascom's assumption that the Hudson River once joined the Delaware River somewhere in central New Jersey.

There has been much discussion among geologists concerning the origin of the "Pensauken gravel,"[1] which extends in a narrow band across New Jersey from Metuchen to Trenton and thence down the Delaware Valley to Salem and Wilmington. R. D. Salisbury,[2] who studied this gravel 50 years ago, was unable to determine satisfactorily either its origin or the method of its deposition; and it was not until 1933 that Marius R. Campbell and Florence Bascom[3] hit upon an explanation that seemed to fit all the known facts.

Campbell and Bascom explained the peculiar composition and distribution of the "Pensauken" formation by assuming that the Delaware and Hudson rivers had once followed different courses in their lower reaches from those which they now pursue, so that they had joined somewhere between Metuchen and Princeton and had flowed southwestward from their junction to Trenton and thence down the present lower valley of the Delaware River to enter Delaware Bay in the vicinity of Wilmington and Salem, depositing the "Pensauken gravel" in their joint valley from their place of confluence to the sea. These authors presented much evidence in support of this explanation and argued that the combined Hudson and Delaware rivers had occupied this valley for a long time during the Cenozoic era, until deflected into their present youthful lower valleys by Pleistocene ice.

The ancient channel of the Delaware above its junction with the Hudson was

[1] The "Pensauken gravel," as the term has been used by various authors, may include two gravels, one of Tertiary age and one of Pleistocene age. The "Pensauken gravel" which is discussed in the present paper is the one which is distributed from the mouth of the Millstone River southward to the Delaware River and down the Delaware. The gravels found in the valley of the Raritan River, downstream from the mouth of the Millstone River, which have been called "Pensauken," may not have been deposited at the same time as those discussed here.

[2] "Surface Geology: Report of Progress," *Ann. Rept. Geol. Surv. New Jersey for 1893 and 1894*, pp. 33–328 (discussion of Pensauken gravel on pp. 52–60. Also R. D. Salisbury, "The Glacial Geology of New Jersey," *Geol. Surv. New Jersey, Final Rept. State Geologist*, Vol. V (1902) (discussions of "Pensauken gravel" on pp. 190, 541, 715, 722, and 741). R. D. Salisbury and George N. Knapp, "The Quaternary Formations of Southern New Jersey," *Geol. Surv. New Jersey, Final Rept. State Geologist*, Vol. VIII (1917) (discussion of "Pensauken gravel" on pp. 67–159). See also Lester W. Shrock, "A Study of the Pensauken Formation," *Bull. Wagner Free Inst. Sci.*, Vol. IV (1929), pp. 3–10.

[3] "Origin and Structure of the Pensauken Gravel," *Amer. Jour. Sci.*, Vol. XXVI (5th ser., 1933), pp. 300–331.

believed by Campbell and Bascom to have extended in a general southerly direction from Port Jervis, New York, through Culver Gap, New Jersey, past Lake Hopatcong, to a point just west of Bound Brook. They were led to this belief partly because of the existence of large gaps through the mountains at Culver Gap and at the southern end of Lake Hopatcong and partly by the presence in the "Pensauken" of many pebbles of black and dark-blue chert, which had evidently been derived from the Upper Cambrian Kittatinny limestone of Sussex County in northwestern New Jersey.[4]

In assuming that these pebbles of black and dark-blue chert came from the Kittatinny limestone of northwestern New Jersey, Campbell and Bascom were undoubtedly right so far as most of the pebbles were concerned; for, although black chert occurs also in the Devonian Onondaga limestone of the Delaware Water Gap region and areas to the northeast of the Gap that were undoubtedly drained by eastern tributaries of the ancient Delaware, some of the Kittatinny cherts differ from the Onondaga cherts in being oölitic, so that they are easily recognized as having come from the Kittatinny formation. There are, however, many other chert pebbles in the "Pensauken gravel" that are buff in color or partly buff and partly black. None of these pebbles is oölitic; and, although it is probable that most or all of them were originally black and have become buff because of very long exposure to the agents of weathering, they look as though they had come from some other formation than the Kittatinny limestone.

No one appears to have undertaken to determine the origin of these buff pebbles, earlier students of the "Pensauken" having apparently assumed that there was no means by which it could be done satisfactorily. Therefore, the recent discovery by the writers that in at least one locality in Princeton Township, Mercer County, many of them contain Onondaga fossils, which indicate that they were derived from the Onondaga limestone of Sussex County, New Jersey, or from adjacent parts of New York, is believed to be worthy of record.

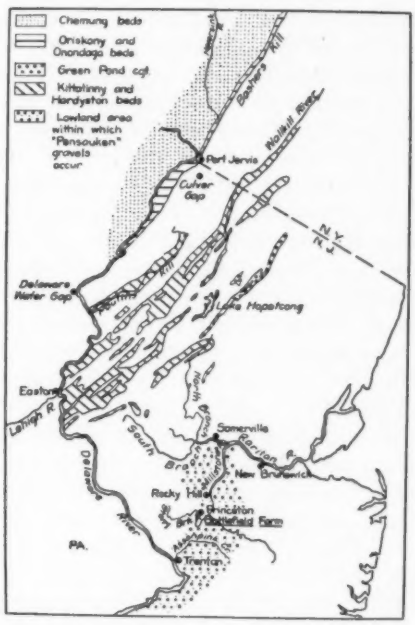


FIG. 1—Map of northern New Jersey and adjacent portion of Pennsylvania, to show distribution of "Pensauken gravel" and of Paleozoic formations, from which fossiliferous pebbles found at Princeton were derived.

These fossiliferous pebbles were found on Battlefield Farm, a part of the site of

[4] Campbell and Bascom appear to have written "Essex County" where they intended to write "Sussex County" in l. 32 of p. 310 of their paper, for there is no Kittatinny limestone in Essex County from which the black and dark-blue chert pebbles to which they there refer could have been derived.

the Revolutionary battle of Princeton. This farm, which was for many years owned by members of Dr. Hale's family, lies on the eastern side of Stony Brook, just southwest of the town of Princeton. The highest land on the farm (where the house is situated) is some 120 feet above sea-level and is composed of "Pensauken gravel." It was from the surface in the vicinity of the house that the fossiliferous pebbles were collected by Dr. Hale. The pebbles are Nos. 57881–57888 and 58192–58300 in the stratigraphic collection of Princeton University.

Associated with the buff-colored chert pebbles containing the Onondaga fossils, Dr. Hale found black chert pebbles (some of them oölitic, but none of them fossiliferous) from the Kittatinny limestone; a few pebbles of other kinds of rocks, whose fossil content or lithologic character indicate that they came from other Paleozoic formations; some pebbles that must have come from the pre-Cambrian rocks of northwestern New Jersey; and a small number of limonitic pebbles that were probably derived from the unconsolidated Cretaceous deposits which are believed to have formed the southeastern (left) flank of the valley through which the combined Hudson and Delaware rivers are thought to have flowed between their point of junction and Trenton.

A careful study of some two hundred pebbles collected from Battlefield Farm enables us to state that, on the evidence of their fossils or of easily recognizable peculiarities of lithology, they had the following origins:

pre-Cambrian (formation undetermined, one pebble contains graphite)
Hardyston sandstone, Lower Cambrian
Kittatinny limestone, Upper Cambrian
Green Pond conglomerate, Silurian
Middle Silurian (formation undetermined)
Oriskany formation, Lower Devonian
Onondaga limestone, Middle Devonian
Chemung formation, Upper Devonian

The identification of the pre-Cambrian, the Hardyston, the Kittatinny, and the Green Pond pebbles is based solely on lithology. All the other identifications are based on fossil evidence. The following fossils were found:

MIDDLE SILURIAN (FORMATION UNDETERMINED)

*Howellella crispa* (Hisinger)

ORISKANY FORMATION, LOWER DEVONIAN

*Acrospirifer murchisoni* (Castelnau)

ONONDAGA FORMATION, MIDDLE SILURIAN

*Favosites turbinatus* Billings
*F. goldfussi* d'Orbigny
*Heterophrentis nitida* (Hall)
*Polypora celsipora* (Hall)
*Chonetes mucronatus* (Hall)
*Atrypa reticularis* (Linne)
*Acrospirifer duodenarius* (Hall)
*Brevispirifer gregarius* (Hall)
*Microspirifer macrus* (Hall)
*Delthyris raricosta* Conrad
*Cyrtina hamiltonensis* (Hall)

CHEMUNG FORMATION, UPPER DEVONIAN

*Leiorhynchus mesacostalis* (Hall)

A single small slab of limestone that almost certainly came from an outcrop of the Kittatinny formation is of special interest because it is so easily soluble and abraded that it can hardly have been carried for any great distance by a stream and must have come from one of the bodies of Kittatinny limestone in Hunterdon, Warren, or Morris counties, New Jersey.

The pre-Cambrian, the Hardyston, and the black chert (including the oölitic black chert) pebbles probably also came from Hunterdon, Warren, Morris, or Sussex counties; and the Green Pond pebbles probably originated in Morris County. The Middle Silurian, the Onondagan, and the Chemung pebbles prob-

ably came from somewhere in New York, as beds of these formations are either lacking in New Jersey or are found only along the New Jersey–New York state boundary. The black Kittatinny limestone chert pebbles are not so well rounded as the buff chert pebbles from the Onondaga limestone, for the Kittatinny pebbles did not travel so far as the Onondaga ones. The present buff color of the presumably once black Onondaga chert pebbles indicates that they were on the road for a much longer time than the Kittatinny chert pebbles, which are always black or bluish-black in color. The Onondaga pebbles, at least, may well have started on their way in Tertiary times.

The land surface from which these pebbles were collected is now some 60 feet above the bed of Stony Brook, which flows near by. As noted above, some of the pebbles on this surface came from northwestern New Jersey and adjacent parts of New York, and those which appear to have come from such New York formations as the Onondaga limestone look as though they had been in transit at least since Pliocene times. As no marine fossils have been found in the matrix of the "Pensauken gravel," it was probably transported entirely by fresh waters. The pebbles on Battlefield Farm could hardly have been brought there by the present Delaware River, whose bed is at sea-level at Trenton. They could not have been brought there by Stony Brook, whose headwaters do not extend far enough northward to have gathered them from their parent-ledges. They show no evidence of having been picked up by a glacier and either transported by it to Battlefield Farm or delivered by it to an ancestor of Stony Brook, which, then flowing at a higher level, might have deposited them in their present resting place. It seems almost certain that they, like the rest of the pebbles of the "Pensauken gravel," must have been rolled along in the bed of a large river of Tertiary or very early Pleistocene age[5] whose headwaters were in New York and which was later deflected from its ancient channel in New Jersey by Pleistocene ice (and possibly also by crustal warping), so that only its gravels remain to mark its course across central New Jersey.

In other words, the evidence of our Battlefield Farm pebbles supports Campbell and Bascom's theory that the ancient Delaware flowed southward from Port Jervis across northwestern and central New Jersey to the vicinity of Trenton. No other theory affords a satisfactory explanation of the presence of these pebbles at Battlefield Farm. Indeed, the proof afforded by their fossils of the sources of many of the pebbles greatly increases the probability that the Delaware once followed such a course.

Our pebbles do not, as far as we have been able to observe, present any clear evidence that the waters of the Hudson River also flowed over Battlefield Farm, as Campbell and Bascom postulated. Some of our pebbles may have been delivered to the Hudson by western tributaries and then transported to Princeton via an old channel of that river, such as was postulated by these authors; but, since the pebbles may have been carried from their parent-outcrops more easily

[5] P. MacClintock and H. G. Richards ("Correlation of the Late Pleistocene Marine and Glacial Deposits of New Jersey and New York," *Bull. Geol. Soc. Amer.*, Vol. XLVII [1936], p. 335) consider the "Pensauken gravel" to be of early Pleistocene age. Richards ("Correlation of Atlantic Coastal Plain Cenozoic Formations: A Discussion," *Bull. Geol. Soc. Amer.*, Vol. LVI [1945], p. 402) states more specifically that it is probably "Nebraskan to Yarmouth" in age, "thus representing both glacial and interglacial stages."

by the waters of the ancient Delaware, we have no reason to assume that they were brought to Princeton from the Hudson watershed. A single piece of serpentine, found by Dr. Hale, looked as though it might have come from the body of serpentine near Boonton, New Jersey, whence it might have been transported to Princeton via the lower valley of the ancient Hudson; but this piece was not a rounded, water-worn pebble, and it may have been carried to Battlefield Farm by man.

It is very desirable that additional collections of pebbles—especially of fossiliferous pebbles—be made from the "Pensauken gravel" at other localities; for such collections, when their fossils have been identified, may afford definite evidence concerning the late Tertiary and early Pleistocene history of central and northern New Jersey. When more such collections have been secured and studied, we shall probably be able to complete the proof of the existence of an ancient Delaware River that flowed well east of the present Delaware between Port Jervis and the vicinity of New Brunswick; and we may be able to determine with certainty whether the ancient Hudson, too, flowed westward to join the Delaware near New Brunswick and go with it past Princeton to the present Delaware Valley near Trenton and so, via Delaware Bay, to the sea.

J. B. Lucke[6] has presented evidence of the existence of a pre-"Pensauken" river that flowed from the northwest across New Jersey and into Raritan Bay. The river which deposited the "Pensauken gravels" may well have followed originally the course of this older stream almost, or quite, to its mouth and may later have been deflected westward by the early Pleistocene Jerseyan glacier and by coastal warping, so that it flowed past Princeton to the lower Delaware Valley from Jerseyan times until the date when the Delaware River began to follow its present course from Port Jervis to Trenton. MacClintock and Richards[7] have called attention to the presence, beneath Jerseyan till in some localities in central New Jersey, of gravels and sands that may have been deposited in the valley of such a pre-"Pensauken" river as Lucke has postulated.

If future discoveries indicate that the ancient Delaware flowed across central New Jersey and down the lower valley of the present Delaware River to the ocean, it will be necessary to give that river a name. As the name "Pensauken" is not available, there being already a Pensauken Creek in New Jersey, and as "Princeton" would be a logical and appropriate name for such a stream, we propose that it be called the "Princeton River."

It is very desirable that a geophysical survey be made to determine the course and depth of the valley of the stream that once flowed through Culver Gap and probably ran past Lake Hopatcong. If the location and the elevation at a number of points of the rock floor of this old valley can be determined by geophysical soundings (as they probably can be), the final evidence of the course, and much information about the age and size, of the river will be secured. It is hoped that such a survey will be made in the near future.

[6] "Gravel Indications of New Jersey Drainage Changes," *Jour. Geomorph.*, Vol. IV (1941), pp. 265–84.

[7] Pp. 229–300, Pl. I, Fig. 2, of ftn. 5.

# GLACIAL BASTIONS IN NORTHERN COLORADO

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ABSTRACT

Three well-developed glacial bastions in northern Colorado are described, their age and mode of origin indicated, and their similarity to glacial bastions elsewhere stated. Bastions in other areas in North America are mentioned.

## INTRODUCTION

Although glacial bastions are by no means rare features of European glacial landscape, many standard texts make no mention of them.[1] Because of this omission, many students, and not a few professional geologists, are quite unacquainted with these features in the continental United States.

During field work in the mountainous portion of northern Colorado[2] a number of bastions and a larger number of bastion-like features were found. Three of these, which were investigated in some detail, will be described. Locations are shown in Figure 1.

## MONITOR ROCK

Monitor Rock, located at the junction of Monitor Gulch with Lake Creek, about $2\frac{1}{2}$ miles WSW of the Twin Lakes post office, in Lake County, Colorado, was accurately described, although not designated as a bastion, by S. R. Capps in 1909.[3] This area is somewhat sketchily shown on the United States Geological Survey Leadville Quadrangle sheet (1/125,000 [1891]). An excellent photograph of Monitor Rock by Westgate, which was used in Capps's report, is reproduced as Figure 2.

Monitor Rock is composed of hard, fine-grained, light-colored granite (field classification), remarkably free from joints. Its height is approximately 350 feet; and at the top the structure projects about 150 feet into the valley of Lake Creek. The upper surface is grooved and striated parallel to the axis of Monitor Gulch; the face, although polished, is not grooved or striated. Well-developed glacial grooves, parallel to the axis of Lake Creek Valley, are present in many places between Twin Lakes and Independence Pass. Local topographic relations are sketched in Figure 3.

Field studies indicate that the grooving and striations on Monitor Rock date from one or more of several mid-Wisconsin glaciations, roughly homologous with W. D. Jones and L. O. Quam's Park Border Moraines[4] or with R. L. Ives's River-Arapaho sequence.[5] The upper

[1] A notable exception is O. D. von Engeln's *Geomorphology* (New York, 1942), which includes a brief clear description (pp. 459–61) and an excellent illustration (Fig. 268).

[2] Field work in part assisted by grants from the Penrose Fund of the American Philosophical Society.

[3] "Pleistocene Geology of the Leadville Quadrangle, Colorado," *U.S. Geol. Surv. Bull. 386* (1909), p. 57.

[4] "Glacial Land Forms in Rocky Mountain National Park, Colorado," *Jour. Geol.*, Vol. LII (1944), pp. 217–34.

[5] "Glacial Geology of the Monarch Valley, Grand County, Colorado," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), pp. 1045–66; and "Glacial Geology of the Colorado Headwaters Area, Colorado" (in preparation). Field checking in the Colorado headwaters area by Quam and in the Estes Park area by

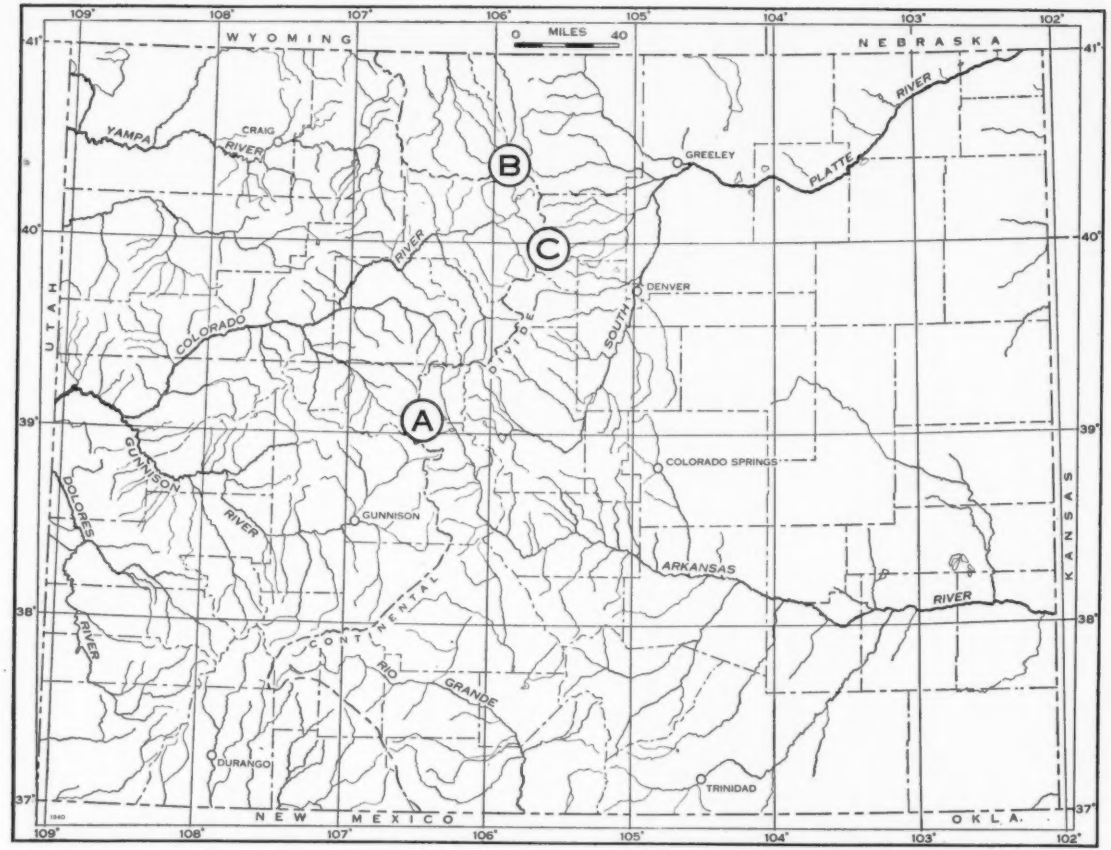


FIG. 1.—Outline map of Colorado, showing locations of bastions studied. *A*, Monitor Rock; *B*, the Hitchens Gulch bastion; *C*, the Silver Lake bastion.

Fig. 1.—Outline map of Colorado, showing locations of bastions studied. *A*, Monitor Rock; *B*, the Hitchens Gulch bastion; *C*, the Silver Lake bastion.

Fig. 2.—Monitor Rock, in Lake Creek Valley, Colorado, seen from the west. This excellently developed bastion is plainly visible from the Twin Lakes–Independence Pass road and is one of the very few easily accessible bastions in Colorado. (After Westgate.)

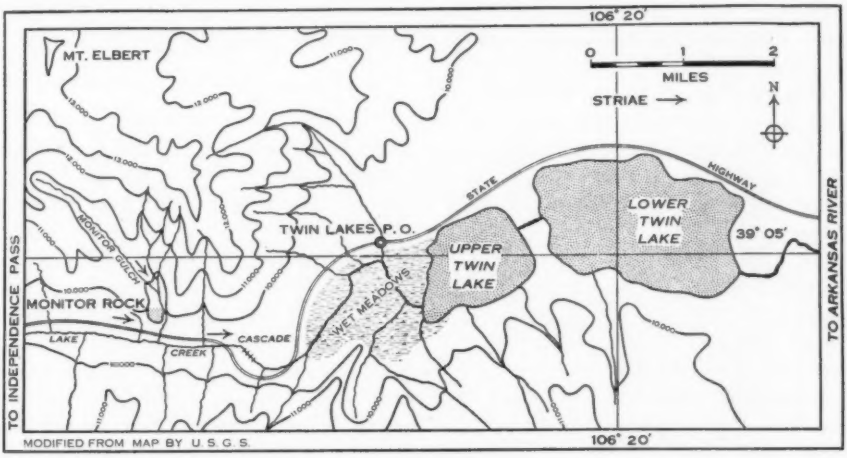


Fig. 3.—Sketch map of Monitor Rock and vicinity, showing drainage, directions of striae, and principal local features.

border of the ice in Lake Creek Valley at that time was approximately 100 feet above the top of Monitor Rock; and the ice in Monitor Gulch, a few hundred feet upstream from the junction, was about 200 feet thick.

Although there is no good reason to believe that the ice in both valleys did not attain maximum thickness at the same time, all that is shown by field evidence is approximate simultaneity.

### THE HITCHENS GULCH BASTION

The Hitchens Gulch bastion is located on the north side of the gulch, which is near the head of the Colorado River, in the Never-Summer Range, Grand County, Colorado. This area is shown on the United States Geological Survey, *Rocky Mountain National Park*, quadrangle map (1/125,000 [1909]; specific location SW. $\frac{1}{4}$, Sec. 35, T. 6 N., R. 76 W.), which is not very accurate at this particular place. One view of the form comprises Figure 4.

This bastion, composed of hard volcanic breccia, is about the same size as the Lake Creek bastion, exact measurement being difficult, as the base is concealed by talus, moraines, and rock-glacier materials.[6] No glacial striae were found on the upper surface or on the face of this bastion. Because the rock weathers rapidly, such surface features are not likely to be preserved.

In the absence of better evidence, this rock boss was assumed to date from the last glaciation which had an upper ice surface above the top of the bastion. Reconstruction of ice profiles in the area indicates that this was not later than the River glacial stage, first of three mid-Wisconsin advances. So old is this boss that the cirque in the tributary valley above it has been largely removed by erosion and landslips.

Field evidence suggests that an ice cascade, of short duration, passed over the east (right, Fig. 4) side of this bastion after the main profile was completed. Because of the nature of the rock at this site and the relatively long time since any ice passed over the bastion it cannot be stated whether the time interval between the formation of the main bastion and the existence of the ice cascade was a few dozen or a few thousand years.

Several other bastions, poorly preserved, and perhaps not very well developed originally, are present in this and adjacent valleys. All, so far as can be determined from the evidence now available, are about the same age.

### THE SILVER LAKE BASTION

The Silver Lake bastion is located on the south wall of the Silver Lake Valley, about $2\frac{1}{2}$ miles down-valley (east) from the Arapaho Glacier. This area is shown (quite accurately) on the *Rocky Mountain National Park* topographic sheet (specific location NW.$\frac{1}{4}$, Sec. 30, T. 1 N., R. 73 W.). This valley has been studied in considerable detail by a number of workers during the last four decades. A summary report on the area is in preparation.[7] Figure 5 shows the Silver Lake bastion and its surroundings.

The Silver Lake bastion is composed entirely of Boulder Creek granite, which is very resistant to all forms of erosion, but which has a well-developed set of joints, which here strike S. 70° E. and

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Ives indicates that the Park Border moraine sequence of Estes Park is homologous with the River-Arapaho moraine sequence of the Colorado headwaters area.

[6] R. L. Ives, "Rock Glaciers in the Colorado Front Range," *Bull. Geol. Soc. Amer.*, Vol. LI (1940), pp. 1271–94.

[7] R. L. Ives, "Glaciation in the Silver Lake Valley, Colorado" (in preparation).

FIG. 4.—The Hitchens Gulch bastion, seen from the southeast

FIG. 5.—Infrared photograph of the Silver Lake Valley from North Arapaho Peak (13,506 feet), showing major features of a complicated, multiply glaciated valley. The bastion is visible in the center of this view, to right of lakes. Note glaciated bench on left side of valley. Moraine of Arapaho Glacier is visible in lower-left foreground.

dip approximately 45° (see Fig. 5). Along these joints, blocks of granite break away rather easily, so that glacial erosion of the south wall of the valley was largely by quarrying rather than by abrasion.

The upper surface of this bastion is covered with a thin layer of alpine soil, which supports a lush growth of grass. Exposed rock is beautifully polished, but not striated or grooved. A few small potholes are present in this area and are attributed to weathering rather than to stream-of-glacier erosion. Rock beneath the soil, as exposed in several excavations, is smoothly polished, but also neither striated nor grooved.

The face of the bastion is neither glacially polished nor striated, in most places, but consists of smooth planes produced by parting along the steeply dipping joints (locally called "stratification").

The tributary glacier which once flowed over this bastion had its source in a small valley near the summit of Bald Mountain (12,753 feet MSL, SE.¼, Sec. 25, R. 1 N., R. 74 W.). Reconstruction of glacial profiles indicates that the bastion was formed during a stage when the valley floor was about 250 feet above its present level. This condition could not have prevailed later than the building of the Albion moraine, oldest and largest of the three attributed to mid-Wisconsin glacial advances (beyond lakes, Fig. 5). It is quite probable, although not rigorously shown by field evidence, that ice cascaded over this structure from the relatively small and feeble Bald Mountain Glacier during one or more later glacial advances, producing a typical ice cascade.[8] During the latest group of Wisconsin glaciations, which built the moraines about and between the lakes in Figure 5, this tributary valley was not glaciated.

[8] Fig. 268 of ftn. 1.

### BASTIONS IN OTHER AREAS

Numerous reconnaissances have disclosed that there are other glacial bastions in Colorado, such as the group near the headwaters of Middle Boulder Creek,[9] and that many can be found in the Uinta, Wasatch, and Sierra Nevada ranges. Unfortunately, most of these structures are in extremely inaccessible locations, and a few are in valleys not even shown on the inadequate maps available today.

Study of a large number of aerial photographs from the western United States, Alaska, South America, and the Himalayan regions suggests that, although no large glaciated mountain region is without bastions, they are not present in all valleys and that, in intensely glaciated regions, one bastion may be present for each four major glacier systems.

### FORMATION OF BASTIONS

Bastion formation cannot be observed directly, for it occurs under a relatively thick cover of ice. While it may be possible, by geophysical methods, to locate a bastion beneath a present glacier and to study the changes in its configuration by remapping every generation or so, this has not been done to date nor, so far as known, has it been attempted.

Inference from physical theory indicates that a bastion may form wherever a tributary joins a trunk glacier if: (*a*) a discordance of levels exists or is produced and (*b*) the lateral thrust of the tributary inhibits lateral erosion by the trunk glacier beneath the junction.

[9] A thorough study of this area, by Dr. P. G. Worcester of the University of Colorado, is now in progress.

Because bastions are not always formed when these conditions would seem to have been met, a number of experiments, in which the bedrock was simulated by wet casting sand, and the ice by a cohesive mixture of Jello and corn syrup,[10] were undertaken. These indicate that bastion-like shapes are usually produced in the sand by simulated ice motion when the angle included between the upstream portions of the two "glaciers" exceeds 40° and when the base of the tributary is above the center of the simulated trunk "glacier." However, because of the difference in properties and in scale between the experimental materials and those in nature, this limiting angle, although seemingly within reason, may have little geologic significance.

Although deepening of the main valley where constricted by a bastion is called for by the "law of adjusted cross sections," and has taken place in many field cases, it was not produced by these experiments.

[10] Although this mixture has many of the properties of ice, including regelation, its use is extremely messy, as the compound ferments, acquires a nauseating odor, and attracts insects. Addition of one-fourth of 1 per cent arsenious acid to the mixture reduced these difficulties considerably. A mixture of neoprene "latex" (costly) and machine oil was also tried with some success.

## CONCLUSIONS

Glacial bastions occur in the United States as well as in Europe and Alaska, and it is probable that some bastions are present in all large glaciated mountain areas as normal landscape features.

Field evidence and experiments indicate that bastions are formed when a tributary glacier at a relatively high level inhibits by its thrust the lateral erosion by the main glacier at the point of junction.

It is the opinion of this writer that the apparent rarity of glacial bastions is due more to lack of recognition than to nonoccurrence and that, when more thorough studies are made of the higher and less accessible portions of glaciated mountain ranges, this apparent rarity will disappear. Much information on this subject could be secured by a thorough study of the aerial photographs now in the files of the War and Navy departments.

ACKNOWLEDGMENTS.—The writer is indebted to Dr. François E. Matthes, of the United States Geological Survey, for many helpful and informative discussions of glacier mechanics; to the late Captain George Langham, A.C., for a reconnaissance flight over the Uinta Mountains; and to M/Sgt. Israel M. Weinberg, Q.M.C., for the procurement, preparation, and disposal of five hundred pounds of simulated ice used in experimental work.

# DISCUSSION: THE ORIGIN OF NEPHELINE ROCKS IN ONTARIO

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Students of the feldspatshoidal rock have reason to welcome the recent activity of the aluminum and ceramic industries in the Bancroft and Methuen districts of Ontario. This activity has not only stimulated the geological mapping of the country and yielded valuable three-dimensional evidence from boreholes, but it has revived a healthy controversy about the genesis of the nepheline-bearing rocks.[1]

A geological map of the Bancroft area on the scale of 1,800 feet to 1 inch was made by F. Chayes and published in 1942. A new map of the same area has since been made by W. K. Gummer and S. V. Burr for the Aluminum Company of Canada and the American Nepheline Corporation; this was published on a scale nearly three times that of Chayes' map, and it is correspondingly richer in detail. Chayes has acknowledged that "the Gummer-Burr map is characterized by considerably less extrapolation than mine; and its location of specific outcrops or quarries is in general to be preferred." It is natural to inquire whether the new study of the area has led to a fuller understanding of the genetic problem.

In the matter of petrography, Gummer and Burr have found little to add to the accurate descriptions given by Chayes and by the great pioneers, Adams and Barlow. There are some changes of nomenclature which tend to obscure a fundamental agreement, as explained below.

The "paragneiss and schist" of Gummer and Burr is the same rock formation as the "syenite and shonkinite" of Chayes. These names were used by Chayes in a purely mineralogical sense to cover a complex of intrusive and hybrid rocks which could not be separated in mapping. Chayes wrote that "the hybrids are streaky heterogeneous gneisses of shonkinitic composition."

The "nepheline paragneiss" of Gummer and Burr comprises those younger or second-degree hybrids to which Chayes gave the mineralogical names "foyaite," "ijolite," and "jacupirangite." Chayes wrote that these rocks "seem to have been formed by the injection of urtite magma into previously solid amphibolite and syenite."

There is little doubt that most of the rocks in question were formed from original sediments and are therefore paragneiss, but some of them may be orthogneiss, either contaminated granite or amphibolized gabbro, as Adams and Barlow suggested and as Chayes too indicates. For this reason it seems undesirable to insist on the prefix "para" when referring to the series as a whole. What is needed is a very wide blanket name such as "Bancroft migmatite series," with recognition that the series is made up of paragneiss, orthogneiss, and migmatite of many kinds. Only a small part of this series is nepheline-bearing.

The matter which specially interests us is the genesis of nepheline in these

[1] See especially W. K. Gummer and S. V. Burr, "Nephelinized Paragneisses in the Bancroft Area, Ontario," *Jour. Geol.*, Vol. LIV (1946), p. 137, and other references therein.

gneissic rocks. There are two main kinds of nepheline-bearing rocks in the Bancroft area: the pegmatites, which have a very simple composition (if we disregard trace elements), and the schistose foyaite or nepheline gneiss, which has a wide range of chemical and mineralogical composition. Chayes claimed that the schistose foyaite was formed by the injection of an urtitic liquid (that is, a liquid having nearly the composition of nepheline) into syenite and amphibolite. A similar opinion regarding the nepheline gneiss at Egan Chute was expressed by F. F. Osborne in 1930. Chayes was able to show that the nepheline-bearing gneiss in the Bancroft district passes by simple decrease in the frequency of the urtitic folia into syenitic gneiss containing only occasional "eyes" or lenticles of urtite and then into nepheline-free gneiss. In Chayes' words, these observations "afford the most convincing evidence of the permeation of syenite by an urtitic liquid."

Chayes argued that this urtitic liquid "was in some fashion derived from the parent liquid of the granites and pegmatites" and further that "the mineralogy of the Haliburton-Bancroft field favors the limestone-syntexis hypothesis" of R. A. Daly. But Keith, Gummer, and Burr maintain, in opposition to Chayes, that the granite is younger than the nepheline rocks and intrusive into them; they hold that this refutes or puts difficulties in the way of limestone syntexis. All that the evidence entitles them to say, however, is that *some* of the granite is younger than the nepheline rocks. Chayes observed that these rocks are in some instances cut by granite-pegmatite, but he recognized that this dates the *end* of the period of granitic intrusion, not its beginning. The limestone-desilication hypothesis does not require that the whole of the reacting magma be desilicated; indeed it has been shown repeatedly that the proportion of feldspathoidal rock formed in any complex is only an inconsiderable fraction of the magma involved. Chayes computed that the whole amount of saturated and undersaturated rock in the Bancroft area constitutes no more than 1 per cent of all the eruptive rock present. Is it difficult to believe that an early intrusion of granitic magma reacted locally with limestone and that later injections of the same magma sometimes intersected the earlier rocks?

Try as he may to avoid limestone-syntexis and desilication of granitic magma, every petrologist who has studied the Bancroft area has been compelled to recognize this reaction sooner or later. Gummer and Burr claim that "there is no field evidence . . . . of the production of nepheline-syenite magma through reaction between solid limestone and granite magma"; but two pages further on they confess that "it is impossible to escape the conclusion that calcite has played some prominent role in the formation of the nepheline rocks." In another place they say that "the nepheline rocks were formed *in situ* by some process of replacement" and add that "the introduced materials contained soda and alumina and apparently not much silica." They favor the idea that the soda and alumina were derived from a granitic or syenitic source, but they do not try to explain how a granitic differentiate can be so poor in silica as to generate nepheline instead of albite in the rocks which it invades.

It is to be regretted that Gummer and Burr are so reluctant to admit the direction toward which they are driven by their own observations. They say "if the nephelinizing solutions were actually albitizing solutions which underwent de-

silication through reaction with $CaCO_3$ . . . . then the reaction was outwardly similar to Daly's postulate." Outwardly similar? The reaction that they describe in the foregoing sentence is Daly's reaction and nothing less!

The nepheline-forming solution pictured by Gummer and Burr seems to be little if at all different from Chayes' urtitic magma. The latter should not be thought of as molten nepheline but as a hot aqueous solution of soda, alumina, and silica in the proportions of 1:1:2 or more (but less than 6). In the field the writer formed the impression that the solutions which generated nepheline in the gneissic rocks were the same solutions which generated the nepheline pegmatites. Indeed the little eyes and lenses of urtite in the gneisses are just small bodies of nepheline pegmatite. Chayes too concluded that "the pegmatites were the source of the nepheline now found in the gneisses"; and so did Osborne at Egan Chute. But because nepheline pegmatite sometimes cuts the nepheline gneiss, Gummer and Burr think that a different origin is indicated. They suggested in 1943 that "many of the nepheline pegmatites appear to be the result of the regeneration of the nepheline of the paragneisses." This idea is put forward again in the later report, but only as a speculation. It appears to the writer, as it did to Chayes, to be unjustified. Nepheline is so easily hydrolyzed that its regeneration "in the presence of introduced materials" (which can mean only water) is highly unlikely.

We must now give some attention to the view of Louis Moyd.[2] Moyd says first that "most of the nepheline-bearing rocks are migmatites, formed from pre-existing rocks of the Grenville series." In this he is in accord with all recent students of the subject. He next pictures the intrusion of granitic magma into the Grenville and says, "some of the magma would react with the dolomitic marbles, releasing emanations [which would] lose much of their silica, forming granitic and syenitic migmatites, and finally, impoverished in silica, would form more unusual migmatites." Since any further reduction of silica, beyond the syenitic stage, must lead to the generation of nepheline, this is just Daly's hypothesis all over again; but now a curious twist is introduced. Moyd says that "these mineralizer-rich emanations could convert the high-lime feldspars of the dark gneisses to alkali-feldspars, releasing alumina to form nepheline or corundum." Since the emanations have already been desilicated far enough to yield potential nepheline, one wonders why it should be thought necessary to bring lime-rich feldspar into the matter and indeed what authority there is for assuming the presence of this kind of feldspar in the Grenville rocks. If Moyd were describing a replacement which he had observed under the microscope, then his statement might be accepted without question—we shall see that this very replacement has been observed elsewhere—but the printed abstract suggests that Moyd is offering us a speculation, not an observation. The one essential factor in Moyd's discussion is just Daly's reaction.

The term "nephelinization" has been used by recent writers to describe the generation of nepheline in the Bancroft gneisses. According to Gummer and Burr the new term is used "to specify the end-result, and does not imply that nepheline was, or was not, added as such." (Nepheline could not be added "as such,"

[2] "Petrology of the Nepheline and Corundum Bearing Rocks of S.E. Ontario," abstract in *Bull. Geol. Soc. Amer.*, Vol. LVI (1945), p. 1183.

because the name is only applicable to the crystalline solid, not to a solution.) Although the term "nephelinization" is new, the idea that a solid rock may be impregnated with nepheline by solutions derived from a later intrusive is not new. As long ago as 1891, J. H. Sears described the essexite of Salem Neck, Massachusetts, and noted the presence of "numerous patches of elaeolite and perhaps sodalite" within the large plagioclase crystals. The observation was confirmed by Rosenbusch (1907); but C. H. Clapp described the mineral as microperthite.[3] The writer has treated thin sections of the Salem essexite with phosphoric acid and methylene blue and finds that the foreign substance in the plagioclase is gelatinized and stained with the same ease as nepheline. Since analcime and sodalite are excluded by the refractive index, the substance can be only nepheline.

These observations seem to fall into line with Moyd's speculation. But Rosenbusch observed, and the writer confirms the observation, that the rocks which show these intergrowths of plagioclase and nepheline are cut by dikes of foyaite which clearly furnished the necessary sodic solutions. Whether the intergrowths were formed by ionic substitution of $Na_2$ for Ca or by simple deposition of nepheline in cracks in the plagioclase crystals has not been clearly established. But since the foyaitic source rock itself contains nepheline, it cannot be maintained that reaction with plagioclase is a necessary step in the generation of nepheline. Nothing resembling these plagioclase-nepheline intergrowths has been observed in the Bancroft migmatites.

The Bancroft area has now been mapped and studied perhaps more closely than any other area of nepheline-bearing rocks in the world, and at least nine geologists (all those who have placed their conclusions on record) have failed to find any substitute for Daly's hypothesis of the genesis of the nepheline rocks in this area.

[3] *U.S. Geol. Surv., Bull. 704* (1921), p. 124, and Pl. XVIII.

# REVIEWS

## NEW SCIENTIFIC DATA FROM FINLAND

With the restoration of mail service, the Finnish workers in earth science have sent abroad many brochures and monographs, in number and quality truly astonishing when one reflects on the grievous conditions of scientific research for seven years. These publications have been issued in journals and other series which are not readily accessible to many geologists and geophysicists in North America. Even a brief and incomplete notice of leading results from some of the investigations may therefore be useful to readers of the *Journal of Geology*.

The first work to be here listed is V. Tanner's 907-page, large-octavo book entitled *Outline of the Geography, Life and Customs of Newfoundland-Labrador*, Volume VIII of *Acta Geographica* (Helsinki, 1944), illustrated with 342 maps, diagrams, and photographs. The book, in excellent English, is a remarkably thorough summary of what is known about the physiography, geology, coastal waters, meteorology, botany, zoölogy, anthropology, and human conditions of Labrador, particularly of the 285,000 square kilometers included in that part of the peninsula now under Newfoundland authority—about one-sixth of the peninsula as a whole. The resulting compilation, based on study of more than eleven hundred books and papers named in the Bibliography, has been done with skill and discrimination.

The new field observations recorded were made during explorations in the summers of 1937 and 1939. Their principal object was to work out the "epeirogenic spectrum" of Labrador and to compare it with that of Fennoscandia, which had been described by Tanner in *Bulletin 88 of the Commission Géologique de Finlande* (1930). It was hoped that "the isochronous beach-surfaces and their deposits will be automatically and definitely identified on both sides of the North Atlantic" so as to "enable us to reconstruct the late- and post-Glacial isochronous paleogeographic development in respect of topography, climate, biology, and archaeology for the two northern continents" (p. 234). For reasons patent to anyone familiar with the raised beaches of Labrador, the development of the epeirogenic spectrum was bound to be a much more difficult feat than in Fennoscandia. Such relevant field observations as could be made in the two short seasons still, in 1944, needed further correlation; for this reason only a few notes on the spectrum problem appear in the book. Tanner intends to issue a full report on this subject later.

It is to be hoped that the promised report will contain maps showing localities where heights of the raised beaches are stated. A second clarification is needed in connection with the problem of the marine limit for the emerged belt along the northeast coast. In his exploration in 1900 the present writer found that at any shoreward profile examined the limit is somewhat higher than the highest beach in that profile. This difference of elevation was attributed to the fact that the highest and oldest beach was principally composed of glacial-erratic material, which along the coast was generally so sparse that its concentration required for beach-making (by undertow and downdrag) was delayed until the land had risen several tens of feet. On that assumption, the highest shoreline in the wave-washed belt, an important element in the epeirogenic spectrum, must be established from the upper limit of wave-washing, after due allowance is made for the range of swash and spray-fling. In fact, the marks of the highest shoreline as determined in 1900 are, at the identifiable localities mentioned in the Tanner book, regularly 20 feet to 60 feet higher than the respective highest beaches as leveled by Tanner.

The present writer has difficulty in accepting Tanner's conclusion that all the high Torngat Mountains of northern Labrador were completely overwhelmed by the last (Late Wisconsin) icecap. During the 1900 exploration, traverses of many miles were made over mountains and broad valleys north of Nachvak Fiord. Above the 2,100-foot contour neither the *roche moutonnée* forms nor striations nor erratic material of the kinds and distribution expected, if the whole region had been covered by ice, were

found. Below the 2,100-foot level the effects of powerful local glaciers were conspicuous, but above it similar effects were observed only in cirques and in the troughs leading from cirques. The utter contrast between the firm, fresh, gray ledges of gneisses and schists below 2,100 feet with the deeply rusted, thoroughly frost-shattered Felsenmeer of gneisses and schists above that contour, and continuing to summit after summit, is described in the old field notes and is still vividly remembered. The contrast cannot, of course, be explained by any essential difference of postglacial climate above and below the 2,100-foot level. It may be added that the ice-molded surface found by Odell on one 4,700-foot summit of the central Torngats, farther west, may indicate, as Odell himself remarks, that pre-Late Wisconsin ice was there ½ mile thicker than it was along the Nachvak Fiord but by no means proves that the eastern half of the Torngat Range was entirely covered by the last Wisconsin icecap. Moreover, there seems to be no published evidence that this belt was wholly submerged by any icecap older than the Wisconsin.

Tanner doubts that the postglacial upwarp of the Labrador peninsula still continues. He discounts the testimony of fishermen of the northeast coast, who have insisted that the water on rock ledges opposite their "tilts" on the shore has somewhat shallowed during the lapse of fifty years or so. If his contention is sound, it would seem necessary to suppose that the coastal belt lies outside (northeast of) any hinge line analogous with the Whittlesey hinge line of our Midwest. In such case the contemporary dynamics of northeastern Labrador would differ from that of the Great Lakes district or that of the Baltic region (see Witting below), where present-day warping of the earth's crust has been demonstrated. Clearly, the question of contemporary uplift of Labrador deserves further discussion, and, above all, effort should be made to settle it ultimately by the use of well-established bench marks and also by repeated precise levelings.

Another significant contribution to knowledge is R. Witting's "Landhöjningen utmed Baltiska Havet under åren 1898–1927 (Die Landhebung dem Baltischen Meere entlang in den Jahren 1898–1927)," published in *Fennia 68*, No. 1 (1945) (pp. 1–40). The main text is written in Swedish; an extended summary in German is added. This paper gives the results of its author's determination of the contemporary upwarping of the Baltic region during the thirty years ending in 1927. He had measured the uplift of the same region during fifteen years ending in 1912, with his findings published in *Fennia 39*, No. 5 (1918). His map showing lines of equal uplift between 1888 and 1912 (reproduced on p. 62 of the present writer's *The Changing World of the Ice Age* [New Haven, 1934]) illustrated the differential nature of the movement, the zero-line following roughly the south coast of the Baltic. Thence, northward, eleven other lines, spaced so as to represent successively greater uplift in the amount of 1 millimeter per annum were drawn; the map indicates upwarp increasing to a maximum at the locus of the greatest loading by the Fennoscandinavian icecap. The zero-line, the 1-millimeter line, and the 2-millimeter line of this older map are strongly sinuous. When the data of the thirty-year interval were reduced, that sinuosity was found to disappear, as indicated by the map, Figure 7, of the 1945 paper, where it is also seen that the zero-line is situated somewhat farther north. Witting points out that the new map is intended to give relative changes of level; the absolute changes cannot be stated until knowledge is had regarding any eustatic shift of sea-level between 1888 and 1927.

The outstanding feature of the map is the close approach of the lines of equal uplift with the mapped isobases for the warped shoreline of the Littorina Sea, with the isobases for the marine limit in Fennoscandia, with the lines of equal uplift representing changes of level at bench marks cut in bedrock in 1800, and also with the lines of equal uplift of the land north of the Gulf of Finland, as demonstrated by precise leveling (see map on p. 315 of the present writer's *Strength and Structure of the Earth* [New York, 1940]). It is hard to dispute Witting's conclusion that the contemporary upwarping of Fennoscandia follows the same general pattern as that of the Late Pleistocene upwarping. Can there be any doubt that the deformation of the Fennoscandinavian crust is a result of isostatic adjustment for removal of its last great load of ice?

The isostatic recoil of a deglaciated region is ably discussed in still a third paper (in English) —this by E. Niskanen with the title "On the Deformation of the Earth's Crust under the Weight of a Glacial Ice-Load and Related Phenomena" (*Annales Academiae Scientiarum Fennicae*, Ser. A, Vol. III, *Geologica-geographica*, No. 7 [Helsinki, 1943], pp. 1–22). It is a dis-

cussion based on the theory of spherical harmonics. Niskanen assumes: (1) the truth of the Airy-Heiskanen theory, whereby he explains the depression of Fennoscandia under the weight of the last icecap and the recoil after the disappearance of the ice; (2) the earth's "crust" to be 63.7 kilometers (1 per cent of the earth's radius) or, alternatively, 31.85 kilometers in thickness; having a density of 2.7 and resting on a 1,200-kilometer earth-shell composed of incompressible "eclogitic" fluid with density of 3.3; and (3) thicknesses of ice (density 0.9), supposed uniform, at 2,000, 2,500, and 3,000 meters.

The calculated degrees of basining of the crust under these various loads are presented in tabular form. There is also discussion of the special, arbitrarily chosen, case of an icecap having a radius equal to 9° of earth-arc, the thickness of ice from the center out to 6° being uniformly 2,000 meters and that between 6° and 9° being uniformly 1,000 meters.

It was found that the crustal subsidence at the center of a 30° cap (of uniform thickness) would be nearly the same as that expected if the crust had no strength. However, owing to its actual strength the depression of the crust at the edge of the cap would be only about 45 per cent of that amount, and the basining would extend several degrees of earth-arc beyond the edge of the cap. Much less extended caps would have contrasted effects. At its center the 6° cap would cause the crust to sink by an amount only about 87 per cent of the amount expected if the crust had no strength, the corresponding percentage at the edge of the cap being 40. For a 9° cap the respective percentages would be about 96 and 44. Niskanen found the percentages to be about 50 and 30 in the case of an icecap with a diameter of 5° (550 kilometers). He generalizes as follows: "These results show us clearly, how sharply the depression decreases when [the radius of the icecap] diminishes. This result is in full accord with Jeffreys' assumption as he states: 'Thus we should expect that the compensation of inequalities of horizontal extent small compared with 2000 km would be incomplete.' The limit put forward by Jeffreys with us corresponds to the value [of icecap radius of] 9° = 1000 km." With his underlying assumptions, Niskanen finds no difficulty in explaining the large gravity anomalies in volcanic islands like Hawaii and Madeira and the long belts of anomalies discovered in Hindustan.

Besides the crustal deformation the author discussed the enforced changes of sea-level. He corroborates the view that, before the basined Fennoscandinavian sector began its plastic recoil in Late Pleistocene time, the sea-level itself was considerably deformed in the same sense. For example, a 2,000-meter, uniformly thick icecap with radius of 9° of earth-arc would depress the crust 526 meters at the center of the cap and 239 meters at its edge. Because of the negative attraction of that basin, sea-level at the center would be depressed below its preglacial position 118 meters if the thickness of the "crust" is 63.7 kilometers, and 110 meters if the thickness is 31.85 kilometers. The corresponding depressions of sea-level at the edge would be 48 meters and 66 meters. Hence, in estimating the amount of uplift of the older beaches in the Fennoscandinavian region, one must allow for the fact that the deformation of sea-level must cause an important addition to the effect of crustal deformation. Niskanen notes how such estimates are further complicated because of the eustatic rise of sea-level while those older beaches were being formed.

The author was naturally conscious of the arbitrary nature of his fundamental assumptions. He believes that the facts of observation are better accounted for if the "crust" has a thickness only half the maximum (63.7 kilometers) assumed in his discussion. He expresses his willingness to accept Jeffreys' conclusion that the thick earth-shell below the "crust" has a small degree of strength, thus demanding less sinking under ice-load than that computed when that shell is assumed to be "fluid." In spite of all qualifications, this paper must be rated as another praiseworthy and useful guide to thought about the meaning and mechanism of "isostatic adjustment."

In his paper on "Gravity Formulas Derived by the Aid of the Latitude and Longitude Zones" (*Annales Acad. Sci. Fenn.*, Ser. A, Vol. III, *Geol.-Geog.*, No. 1 [1941], pp. 1–19) N. Luoma has made another attempt to answer the question as to whether the earth's equator (sea-level figure) is elliptical. He used the free-air gravity anomalies determined at 7,138 stations. These were grouped in 10° zones of longitude and also in 10° zones of latitude; and from the groups of every zone gravity formulas were derived. Luoma's conclusion runs as follows: "The results of the various latitude zones do not agree well with one another. But we must add that in omitting the disturbed areas the observed gravity anomalies seem to be in rather good har-

mony with the triaxiality of the equator. It seems to be possible that the difference . . . . of the long and short equator axis is about 150 to 250 m. and that the long equator axis lies about 0° to 20° west of Greenwich."

E. Niskanen discusses the same problem in his "Gravity Formulas Derived by the Aid of the Level Land Stations" (*Annales Acad. Sci. Fenn.*, Ser. A, Vol. III, *Geol.-Geog.*, No. 10 [1945], pp. 1–16). He used isostatically reduced anomalies of the Northern Hemisphere and only those at stations in "plain" area and under 300 meters in height. He also deduced triaxiality for the sea-level figure of the earth, the long equatorial axis exceeding the short axis by 293 meters and emerging about 4° west of the Greenwich meridian. In his summary he remarks: "In the opinion of the writer it seems natural to assume that the triaxiality is caused by the overcompensation of the continents and of the oceans." He of course agrees with all other workers on the earth's figure that final conclusion regarding the ellipticity of the equator is impossible until thousands of new, well-distributed measurements of gravity are made in the Southern Hemisphere.

Finally, three important discussions of gravity anomalies in as many regions of special interest to structural and dynamical geologists will be mentioned. Brief summaries of these can hardly be of much real value; each should be studied carefully from cover to cover. The three memoirs bear the titles:

1. "On the Structure of the Earth's Crust in the Neighbourhood of the Ferghana Basin," by V. Erola (*Annales Acad. Sci. Fenn.*, Ser. A, Vol. III, *Geol.-Geog.* No. 3 [1941], pp. 1–77);

2. "On the Isostatic Structure of the Earth's Crust in the Carpathian Countries and the Related Phenomena," by L. Tanni (*Annales Acad. Sci. Fenn.*, Ser. A., Vol. III, No. 4 [1942], pp. 1–100); and

3. "The Gravity Anomalies on the Japanese Islands and in the Waters East of Them," by W. Heiskanen (*Annales Acad. Sci. Fenn.*, Ser. A, Vol. III, No. 8 [1945], pp. 1–22).

R. A. DALY

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*The Geology of Missouri.* By E. B. BRANSON. ("University of Missouri Studies," Vol. XIX, No. 3 [1944].) Pp. 41; figs. 57; pls. 49. $3.00.

This volume, the second work published under this title by the author, is devoted principally to the stratigraphy and paleontology of Missouri. It takes up in chronological sequence all formations from the pre-Cambrian through the Tertiary and is concluded by sections on the Pleistocene; topography; structural and economic geology, parts of which were written by Chauncey D. Holmes, Cornelia Cameron, and W. D. Keller; and an extensive Bibliography of nearly one hundred pages. The plates, in halftone, all illustrate Missouri fossils. About one-third of them were taken from unpublished papers and illustrate many unnamed new species. The others are mostly reproductions of plates previously published by Branson and associates. The figures include excellent outcrop photographs; a series of outcrop maps, some of which illustrate paleogeographic interpretations; several correlation charts, etc.

Branson's extensive field observations during his many years' residence in Missouri have contributed much to the preparation of this work, but sections devoted to the pre-Devonian and post Lower Mississippian formations are based largely upon the published investigations of others, to which references are made. Branson has been particularly interested in the Devonian and Lower Mississippian rocks of Missouri; and his discussions of these formations present his views regarding correlations and other interpretations, which are not entirely acceptable to some other stratigraphers and paleontologists. This field appears to be beset with important and as yet not completely solved problems, and more objective considerations would have been advantageous.

In general, the treatment of each formation begins with a statement regarding the derivation of its name and the distribution; followed by lithologic description, often including a measured stratigraphic section; discussion of its stratigraphic relations; a list of fossils; and concluded with a paragraph on age and correlation. Inasmuch as nearly ninety named formations are considered and more than one-third of the text in the stratigraphic portion consists of fossil lists, the individual discussions are necessarily brief, and some are hardly adequate. Most of the fossil lists are composite. Generally, sources of the lists are given, but there are no locality data. The author admits (p. 402) that many of the identifications are possibly incorrect. Under these circumstances it may be questioned whether the fossil lists are deserving of so much space. They are intended to be complete, but some inadvertent omissions occur.

This volume is an important compendium of

information on the geology of Missouri and will prove most useful to all geologists interested in that state. Perhaps its chief deficiency lies in inadequate presentation of facts regarding the distribution and detailed stratigraphic relations of some formations. Interpretation of some episodes in the geologic history of the state are presented at various places in the text, but the data do not make possible the reconstruction of a connected history. The very brief section on structural geology is almost entirely descriptive and gives little aid in this direction. Very little information concerning subsurface geology is presented.

J. M. W.

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*Principles of Physical Geology.* By ARTHUR HOLMES. New York: Ronald Press Co., 1945. Pp. 509; figs. 262, pls. 95.

Every author who prepares a textbook knows that the greatest measure of criticism will come not from the students who use the book but from his teacher-colleagues who will peruse it. Teachers of introductory geology will view with utmost respect Holmes's masterly treatment of the *Principles of Physical Geology* for the beginning student. The author's colleagues, after inspection of the book, will feel that little that is essential has been omitted.

The plates mentioned on the title-page in many instances carry two halftone views, and some of the text illustrations involve four or five diagrams. Thus, the author has endowed a book of 509 pages, each page covering an area of $4 \times 6\frac{1}{4}$ inches of type, with at least 425 photographs, line drawings, diagrams, sections, maps, and tables. Through these visual aids to student understanding the American teacher will roam, rather expecting that the European Continent and the British Isles will have furnished a British author with such a plethora of geological illustration that distinctive North American material will hardly find room.

Dr. Holmes, however, has chosen his photographs so judiciously from many parts of the globe that the American reader will find over forty views of well-known North American physiographic features. Included are the Grand and Bryce canyons, Niagara and Yosemite falls, the South Dakota Bad Lands, and Rainbow Natural Bridge. Appalachian mountain structure, the faults and fault movements of the Pacific Coast, the terraces of the Frazier and the delta of the Mississippi River, ice erosion in the Yosemite Valley, and the development of the Great Lakes are all given illustration and comment. He will find that the contributions of Daly, Dana, Davis, Dutton, Gilbert, and others have not been overlooked or ignored. The bibliographies at the ends of chapters contain references to the works of Ford, the Fentons, Willis, Lahee, Schuchert, Dunbar, Lobeck, Von Engeln, and to many other American authors.

In the textual presentation a chapter on continental drift; three chapters on the challenge of earth movements and of mountain building; considerable emphasis on isostasy; and the mathematics involved in determination of earthquake origin, in thermal dynamics, and in the formulas of wave motions stand out in some contrast from the customary treatment of such subjects in textbooks of beginning geology.

The book seems to have been proofread with great care, and but a few typographical errors appear. The paper selected by the publishers does away with the glare of reflected light at night, which often is a serious matter to students. On the other hand, this paper possibly is responsible for the poor reproduction of some of the halftones. The book commands hearty approval and praise for the thorough manner in which the subject is developed. Some American teachers, in using it, probably will need to plead for an extension of the time allotted to geology in their college programs in order to treat the subject adequately.

JOHN R. BALL

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*Geology as a Profession.* ("National Roster of Scientific and Specialized Personnel, Vocational Booklets," No. 1.) Washington: United States Government Printing Office, 1946. Pp. 19. $0.10.

This useful booklet has been prepared by Miss Ann R. Taylor, working under the direction of Dr. W. T. Read, with the advice and assistance of many geologists. It gives the subdivisions of the geological profession, the working conditions and types of employment, the opportunities for women, the related fields of employment, beginning jobs, advancement and conditions of employment, postwar outlook in the profession, and the qualifications and training, and makes suggestions as to how to get a start. The booklet is attractively illustrated. It will be of special value to advisers of young students and, while written primarily from the employment point of view, will also give those

entering the profession a condensed and business-like summary of what they may expect.

Copies may be obtained from the Superintendent of Documents, United States Government Printing Office, Washington 25, D.C.

R. T. C.

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*Mineral Resources of the British Commonwealth.* London: Royal Society, 1946.

During the latter part of June and the first week in July the Royal Society of London held an Empire Scientific Congress dealing with scientific subjects of all kinds. A prominent place was given to discussions on the mineral resources of the British Commonwealth and the need for improved surveys. Copies of the following papers have been received by the *Journal of Geology:*

1. "The Need for a Co-ordinated Survey of the Mineral Resources of the Empire and for Operations on a Much Larger Scale than Hitherto," by Sir Thomas Holland.

2. "The Need for the Survey of the Mineral Resources of the Empire on a Much Larger Scale than Hitherto and for More Up to Date Methods," by Professor E. S. Hills.

3. Same title, M. S. Krishnan and D. N. Wadia.

4. "The Resources of Mineral Raw Products in the Union of South Africa," by Dr. L. T. Nel.

5. "Detailed Geological Mapping and New Zealand Mineral Resources," by E. O. Macpherson.

6. "The Mineral Industry of the Union of South Africa," by S. H. Haughton.

7. "The Need for a Co-ordinated Survey of the Mineral Resources of the Commonwealth (General and Special Recommendations)."

These are short papers of a dozen pages or less. Copies of particular speeches may be obtained by writing to The Secretary, The Royal Society, Burlington House, London W. 1, England.

R. T. C.

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